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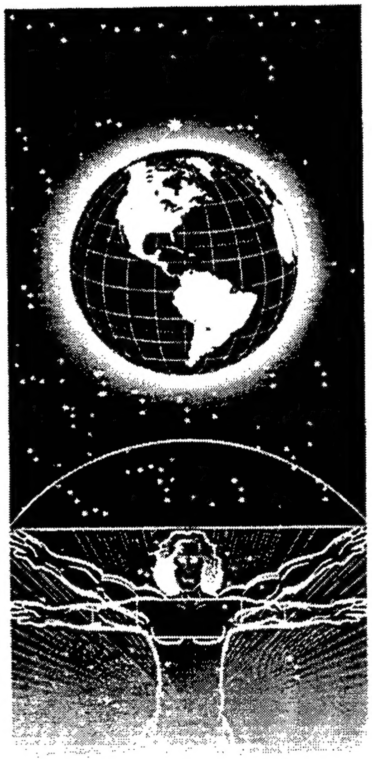

UNITED STATES AIR FORCE RESEARCH LABORATORY

Detailed Research Plans for a Study of Aircraft Noise and Sonic Boom Effects and Measurements
Volume VI: Effects of Sonic Boom and Low Frequency Noise on Structures and Terrain

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This report has been reviewed by the Office of Public Affairs (PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public.

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FOR THE COMMANDER

MARIS M. VIKMANIS
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13. ABSTRACT *(Maximum 200 words)*

This report describes the effort of the US Air Force to develop a master plan to address the impacts of sonic booms on the environment. This report details the known effects of sonic booms on structures and describes the research needed to fill the gaps in sonic boom modeling, measuring, and monitoring.

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1.0 EXECUTIVE SUMMARY

This report constitutes a preliminary version of a detailed research plan, prepared in accordance with the requirements of the Noise and Sonic Boom Impact Technology (NSBIT) program, in the areas of damage effects and response of structures to sonic booms and low frequency noise. This Executive Summary provides a background of the objectives and scope of these areas, and a summary of recommended programs designed to satisfy Air Force needs. The programs are described in detail in Section 4 of this report. Appendices A and B contain a comprehensive technical discussion and literature survey supporting the detailed research plans presented here.

1.1 Objectives

To satisfy operational needs, the Air Force requires the capability to:

1. Support the Environmental Impact Assessment Process carried out for proposed supersonic operations including: (a) the prediction of potential damage to the various man-made and natural structures within the affected areas, and (b) reassurance of the public on the potential structural damage problem of planned supersonic operations.

2. Support Air Force positions during litigation or resolution of claims involving potential damage from sonic booms from existing supersonic operations.

3. Develop improved understanding of building and seismic response to low frequency noise for application to siting criteria for static engine test "hush houses" and for application to new or improved noise metrics for impact assessment guidelines for rural or remote land areas exposed to sonic boom or noise from low altitude training routes.

1.2 Scope

The scope of the research required to satisfy the needs described should include development of the following technology.

- o New or improved technology to address claims, real or hypothetical, of structural damage of the type for which little or no previous data are available.

- Statistical estimates of structural response levels and the resulting stress or damage levels for a much wider range of structures than is available today, including historic or archaeologic sites, water tanks or water wells, and special structures or facilities such as geothermal power generation facilities or large radio telescope antennae.

- Estimates of response of such structures to a wide range of overpressures from 2 psf to as high as 150 psf when the sonic boom loads tend to equal or substantially exceed structural design loads leading to a high probability of structural failure. (Note that the maximum credible overpressure for supersonic flights limited to altitudes above 5000 ft. is about 30 psf in a focus boom, and values as high as 150 psf could occur only if aircraft conduct low level supersonic flights down to 100 ft. AGL.)

- Improved technology for improving communication with the lay public on the topic of potential structural damage.

- Objective measures of the low frequency response of buildings or seismic response of ground that lead to subjective human responses due to visual perception of vibrating walls, windows, etc.; tactile sensations of structural vibration; auditory (or nonauditory) perception of low frequency sound; and auditory perception of rattle noise from loose windows, pictures, dishes, etc., or interference with vibration-sensitive industrial activity.

1.3 Background

Structural Damage Effects of Sonic Boom

Initial studies of structural damage from sonic boom started in the late 1950's as supersonic aircraft came on-line in the Air Force. However, most of the knowledge about structural damage effects was developed during the late 1960's and early 1970's when a vast amount of research was carried out to evaluate the potential environmental impact of the then-proposed SST. This research involved overflight tests over urban areas, controlled field tests in isolated areas, laboratory tests of window or wall specimens, and a wide range of analytical studies to support or guide the experimental work.

At the average overpressure of about 1.8 psf anticipated for SST overflights, the structural damage observed during several simulated SST sonic boom exposure tests over heavily populated areas was very slight — limited primarily to breakage of windows in poor condition and minor damage in the form of small plaster cracks, broken bric-a-brac, etc. Current Air Force sonic boom damage assessment guidelines actually provide an equation for estimating the probability of such window breakage. The low but finite probability of window damage predicted by this equation (of the order of 10^{-6} window panes broken per 2 psf boom) is roughly consistent with current Air Force damage claim experience. Thus, the state of the art predictions for minor damage indicates that there will tend to be an unavoidable and continuing burden of small damage claims due to normal sonic boom environments near supersonic flight training areas. The rate and degree of damage would increase markedly if supersonic flight altitudes were decreased well below 5000 ft.

Several controlled overflight tests were also carried out during the SST program to measure building or seismic responses to sonic booms; most of these tests were for overpressures below 30 psf. Only minor damage (hairline cracks in plaster) occurred on interior walls or ceilings at average overpressures of about 8 psf, whereas more serious damage (falling plaster, tiles) occurred on interior walls at average overpressures of about 12 psf.

Two tests were also conducted at overpressures up to about 100 to 150 psf, but with the exception of tests on isolated window specimens, no complete conventional structures were exposed to these highest levels. In the window specimen tests, approximately 75 percent failed at the highest overpressures. Very few damage data have been collected on atypical structures, such as historical monuments, archaeological structures, and water wells, found in supersonic operating areas.

Laboratory tests of windows, walls or plate specimens to simulated sonic booms generally agree with theoretical models. However, such tests are not realistic unless they duplicate actual in-place stress conditions for the window, particularly at the edges which tend to cause window failure at lower peak overpressures.

Practical, empirically-based statistical models, developed to predict minor damage rates primarily for window breakage and plaster cracking, have been

roughly validated with very limited data. These statistical models predict the observed high sensitivity in failure rate to changes in overpressure. For low overpressures (2 psf or less), peak stresses were generally close to peak values that could occur when slamming a door.

Seismic Response to Sonic Booms

Seismic responses of terrain induced by sonic booms generally fall well below a critical velocity of 1-2 in/sec, considered by the U.S. Bureau of Mines to be the threshold for building damage due to seismic excitation from blasting. Only for sonic boom pressures approaching 30 psf will seismic velocities begin to equal or exceed these structural vibration damage limits. Triggering an avalanche by sonic boom has yet to be demonstrated in controlled tests, but anecdotal data have definitely proven that snow avalanches can, and have, been triggered by sonic booms. While this unusual form of structural (or more properly, terrain) damage from sonic boom is generally localized to mountainous regions in the winter only, the potential consequences of an event could be very serious. Hence this research area has a high priority relative to the likelihood of the phenomena occurring.

Air-coupled seismic waves excited by sonic booms are also of concern. This "resonance" condition is capable of generating a much greater seismic response than would normally occur, but a theoretical study has indicated that it is unlikely to occur. However, one limited experimental evaluation has indicated that such a resonance effect may have occurred, possibly explaining the occasional claims of damage to building foundations or water wells due to sonic booms.

Gaps in Technology of Damage Effects

Based on this status of the knowledge of structural damage effects of sonic boom, major gaps to be filled include:

- Validated models for predicting the triggering of avalanches or landslides by sonic booms.
- Basic data and prediction models to assess the structural damage potential for unconventional structures, such as historical monuments, archaeological structures, water wells, etc., for which little or no data are available.
- Validated prediction models to assess the full range of potential structural damage to conventional structures for sonic boom

intensities including overpressures ranging from nominal 2 psf value up to as high as 150 psf.

- Validated prediction models to assess realistic seismic response anomalies due to coincidental air-coupling of sonic booms and ground surface waves.

The extensive knowlege-base on structural damage from conventional or nuclear blast effects can be tapped to fill some of these gaps but only by taking full account of the significant differences between the transient pressure loads of sonic booms and blast loads.

Low Frequency Response

The non-damaging response of buildings to the low frequency content of sonic booms, intense jet noise from low altitude subsonic overflights, or noise from hush houses can cause several types of subjective human responses due to:

- Visual perception of vibrating windows
- Tactile sensation of vibrating floors or walls
- Rattling noise generated by loose windows or bric-a-brac or the direct low frequency or infra-sonic sound itself.

Analytical and experimental data are available from recent research by NASA and CERL to aid in evaluating these various vibroacoustic and subjective responses. However, these research results are incomplete. The first basic need that exists in this area is a more widely applicable and more completely validated model for the vibroacoustic response of conventional structures to the low frequency content of sonic boom or jet noise. Development of improved understanding of the related subjective responses is considered in Volume IV of these detailed plans.

Low frequency acoustic energy from static engine tests or low altitude overflights can cause troublesome seismic vibration in some locations. Basic theoretical knowledge is growing in this area as a result of current research but this needs to be interpreted in more practical terms for application to Air Force concerns.

1.4 Recommended Programs

The gaps identified above have led to selection of the following five programs on structural and seismic effects of sonic boom and low frequency noise.

The first four programs relating to damage effects are listed in approximate order of priority within this technology area. Figure 1-1 presents an overall schedule for these recommended programs along with a summary of estimated costs.

Structural Damage Effects

Program No. 1: Avalanche/Slide Triggering Evaluation

Objectives:

Develop a practical, validated model for predicting the relative risk of triggering snow avalanches or earth slides by sonic booms.

Scope:

Initially, information will be collected on the history of avalanche triggering by sonic booms or explosives in Canada, Switzerland and the United States. Subsequently, pilot field tests on avalanche triggering will be carried out, leading to a more comprehensive test program in conjunction with the development of a prediction model. A parallel program aimed at earth slides will be undertaken. Selection of test areas and the complexity of final test programs will be based on an initial assessment of relative risk of avalanches or slides occurring in supersonic operation areas and practical constraints on the ability to provide sonic boom environments in the desired locations.

Resources and Schedule:

The program is estimated to cost $570,000 and require 4 years to complete.

Program No. 2: Structural Damage Criteria for Unconventional Structures

Objectives:

Develop practical models for prediction of damage from sonic booms to adobe buildings, archaeological structures, historic monuments, storage tanks, reflector dishes, and water wells.

Scope:

The prevalence of each of the different types of special structures in all supersonic operating areas will be established. Based on these data the relative severity and significance of potential damage to such structures will be rank ordered. Based on this ranking, coordinated analytical studies,

Program Title	Years 1	2	3	4	5	Cost x $1000
1. Avalanche/Slide Triggering Evaluation						570
Phase I - Review & Risk Assessment						
Phase II - Correlate Available Models						
Phase III - Experimental Testing						
Phase IV - Prediction Models						
2. Structural Damage Criteria for Unconventional Structures						637
- Wells						
- Liquid Storage Tanks						
- Adobe Buildings						
- Monuments/Archaeological Structures						
- Radio Astronomy Antennae						
3. Extended Damage Prediction Models for Conventional Structures						606
Phase I - Data Review						
Phase II - Model Development						
Phase III - Field Test Program						
Phase IV - Damage Prediction Model						
4. Seismic/Acoustic Interaction						334
Phase I - Review & Test Plan						
Phase II - Field Validation						
Phase III - Model Development						
5. Low Frequency Structural & Seismic Response						255
Phase I - Rattle Noise Vibration Data Base						
Phase II - Rattle Noise Vibration Prediction						
Phase III - Acoustic-Seismic Vibration						
TOTAL						2.402

Figure 1-1. Overall Schedule and Summary of Costs for Proposed Research Programs on Structural Effects Technology.

with the support of critical experimental validation tests, will be carried out. The overall results of these analyses and tests will be combined into practical damage prediction models.

Resources and Schedule:

The program is expected to cost $637,000 and extend over a 4 year period.

Program No. 3: Extended Damage Prediction Models for Conventional Structures

Objectives:

Develop practical methods for predicting or assessing damage, especially major damage, to an extended range of conventional structural elements.

Scope:

The program will define the expected type, severity and approximate probability of damage, principally major damage to an extended range of conventional structural elements, in addition to windows, due to sonic boom loads. The program would include a thorough evaluation of existing empirical damage data from blast and sonic boom tests, development of a statistical damage prediction model with a wider range of application than previous models, and a carefully targeted test program requiring either a limited number of dedicated supersonic flights or carefully coordinated tests carried out in conjunction with normal supersonic flight activity, to acquire critically needed additional data in support of the final prediction method.

Resources and Schedule:

The program is estimated to cost $606,000 and would extend over 3 years.

Program No. 4: Seismic/Acoustic Interaction

Objectives:

Establish an experimental basis for a prediction model for air-coupled seismic waves.

Scope:

Early analytical models for air-coupled seismic waves will be reexamined to explore seismic responses to sonic booms using more recent knowledge of sonic boom pressure patterns on the ground (see Volume II of these detailed plans), especially from transient maneuver operations, and seismic behavior

of the ground to such patterns. Anticipating the difficulty of conducting any practical type of experimental validation program involving dedicated flights, a validation test program would be carried out over a period of 2 to 4 months in a normal supersonic operating area employing unmanned seismic response measurement systems. This program may be combined with Program No. 3, Phase II under the Sonic Boom Monitoring effort outlined in Volume II of this report.

Resources and Schedule:

The program is expected to cost $240,000 and last for 1 year.

Program No. 5: Low Frequency Structural and Seismic Response

Objectives:

Develop a broad, statistically valid data base and prediction model for non-damaging structural vibration and rattle noise inside conventional structures and seismic vibration of ground exposed to low frequency noise from Air Force flight operations and static test facilities.

Scope:

The program would be designed to include activity in two general areas: (1) rattle noise and vibration due to low frequency excitation of buildings, and (2) seismic vibration due to low frequency acoustic excitation. In both cases, the low frequency noise of primary concern would be that generated by static engine testing. However, the program should also include consideration of low frequency energy from low altitude aircraft flights along military training routes. Seismic coupling of low frequency energy associated with secondary sonic booms (or rumble) well to the side of supersonic flight tracks may also be included if warranted. However, it is expected to have a very low priority at this point.

Resources and Schedule:

The program is expected to require 2 years to complete and would cost $245,000.

2.0 INTRODUCTION – STRUCTURAL EFFECTS OF SONIC BOOM AND LOW FREQUENCY NOISE

The overall technology relating to structural effects is broken down into two broad areas: (1) structural damage effects of sonic boom and (2) structural or seismic response to low frequency noise. The latter refers to the nondamaging response of buildings or the ground to the low frequency content of sonic booms and to structural response (and ensuing subjective response) to low frequency noise from hush houses or low-flying subsonic aircraft. The first area – structural damage effects from sonic boom – is supported by this structural response technology, but it focuses entirely on the problem of potential or actual structural damage from sonic booms. It is the more critical aspect of structural effects and is treated first.

2.1 Air Force Needs

2.1.1 Structural Damage Effects

Expanded supersonic operations anticipated by the Air Force may result in the exposure of more structures to, and the potential for damage to these structures from, sonic boom. To respond effectively to public concern about this problem, the Air Force needs improved technology in order to:

1. Support the Environmental Impact Assessment Process carried out for proposed supersonic operations including: (a) the prediction of potential damage to the various man-made and natural structures within the affected areas, and (b) reassuring the public on the potential structural damage problem of planned supersonic operations.

2. Support Air Force positions during litigation or resolution of claims involving potential damage from sonic booms from existing supersonic operations.

Nominal sonic boom overpressures of primary interest will be limited to less than 30 psf. Such relatively high sonic boom overpressures could occur (but only very rarely) at a focus boom point for supersonic aircraft operating at the normal lower altitude limit of 5,000 ft AGL for supersonic air combat training. Secondarily, there is interest in identifying and evaluating the structural damage potential of low-altitude supersonic flights as low as 100 ft AGL. Such operations would develop overpressures of the order of 100 to 150 psf.

The specific nature of the Air Force need for improved technology on potential structural damage effects of sonic boom is indicated by the public comments on preliminary EISs prepared by the Air Force and the Navy for supersonic MOAs. The public statements about structural damage range from well-founded complaints about the relatively infrequent damage that can actually be caused by sonic booms, to what appear to be highly exaggerated or unrealistic claims of potential damage in anticipation of future operations. A responsive research plan for this technology area must consider all of these potential problems, be they real or imagined, since they represent genuine public concerns.

2.1.2 Low Frequency Response

Four interrelated Air Force needs are involved with the development of improved understanding of how buildings and terrain respond to low frequency acoustic energy, namely:

- o Development of suitable siting criteria for static engine test "hush houses." The acoustic environment for these can be dominated by infrasonic energy (see Volume II of these Detailed Plans).
- o Development of suitable noise impact assessment guidelines (this may require new or improved noise metrics) for exposure of rural or remote land areas to noise from low altitude training routes. The noise signatures involved are expected to have substantial low frequency energy that is not normally experienced by residents near air bases.
- o Development of similar or related guidelines for exposure of rural or remote land areas to sonic boom environments. Again, low frequency (non-damaging) response of structures is expected to form part of the basis for these guidelines.
- o Development of guidelines and prediction models for seismic vibration induced by low frequency noise from static engine testing or sonic boom, that may have significance for vibrationally-sensitive activities or that may contribute to the subjective response of communities to low frequency acoustic energy.

In all cases, the "need" concerns only improved understanding of how buildings or terrain respond to the low frequency energy content involved in each of these situations. Actual structural damage is not involved, although subjective response may assume damage has, or could, occur.

2.2 Required Technology

2.2.1 Structural Damage Effects

To improve predictions of structural damage from sonic booms of moderate level (<30 psf), the Air Force requires the ability to make

- Statistical estimates of structural response levels and the resulting stress or damage levels for a much wider range of structures than is available today, including, in addition to conventional structures, historic or archaeologic sites, water tanks or water wells, and special structures or facilities such as geothermal power generation facilities and large radio telescope antennae. The vast majority of the previous effort in sonic boom damage dealt with window damage or minor structural damage such as plaster cracking. Now it is essential to extend this information to a much broader range of structures and types of damage.
- Estimates of structural response to higher overpressures (from 30 to 150 psf). In this case, the sonic boom loads tend to equal or exceed structural design loads leading to the feasibility of making more nearly deterministic predictions of structural failure.
- Estimates of terrain response to sonic boom, including the probability of triggering snow avalanches or earth slides or the potential or anomalous seismic responses occurring as a result of a "resonant matching of seismic wave speeds and trace velocities of sonic boom pressure waves over the ground."
- Improved technology for improving communications with the lay public on the topic of potential structural damage. This improvement would help to reduce public concern about sonic boom structural damage and minimize the number of grossly exaggerated or uninformed predictions of potential damage.

The degree to which these needs for improved technology can be met necessarily involves cost-benefit considerations. Thus, a practical research program on potential structural damage effects of sonic boom should yield a net cost-benefit by:

a. Reducing the tangible and intangible costs of delays in mandated Air Force missions that can occur when the Environmental Impact Assessment Process fails to establish public acceptance of the structural damage issue.

b. Providing a net reduction in the cost of sonic boom damage claims from current or proposed supersonic flight activity. This includes costs of investigating the damage claims as well as costs of litigation or settlement of claims. The average annual value of the structural damage claims paid by the Air Force since 1962 is estimated to be about \$140,000 per year. However, the total cost, including costs of manpower and legal fees in processing the claims, may have been of the order of \$1 million per year or more. Today, there is a more liberal climate in the courts for awarding damages, and thus the total cost for claims paid may tend to increase.

2.2.2 Low Frequency Response

Low frequency response of buildings leads to subjective responses elicited by visual perception of vibrating walls, windows, ceilings, and floors, tactile sensations, auditory (or non-auditory) perception of direct acoustical radiation of low frequency sound through vibrating surfaces, and auditory perception of indirect acoustic radiation from rattling of loose windows, or internal furnishings (pictures, dishes, etc.). To assist in understanding these subjective response patterns, the technology required should provide quantifiable and objective measures of these vibroacoustic structural responses that can be utilized in portions of the proposed research program relating to human response (see Volume IV). Depending on the application, it will be desirable to have available methods to either measure or predict these vibroacoustic structural responses.

Finally, methods are needed for evaluating seismic responses of the ground to low frequency noise from static engine test facilities (e.g., hush houses), low altitude flyovers from military training routes or from sonic booms. In this case, the critical responses may relate to vibration-sensitive activity (such as high precision manufacturing processes) or human perception of such seismic responses which can compound the subjective response as outlined above.

3.0 TECHNICAL BACKGROUND

3.1 Summary of Current Technology

The following is a summary of the current understanding of structural damage effects and low frequency response. A more complete review is provided in Appendix A.

3.1.1 Structural Damage Effects

With the exception of a pioneering study in 1959 (Arde Associates, 1959),* most of the knowledge about structural damage effects of sonic boom was developed during the late 1960's and early 1970's, when a vast amount of research was carried out to evaluate the potential environmental impact of the then-proposed SST. This research involved the following:

- Controlled overflight tests
- Laboratory tests of window and wall specimens
- Analytical studies to support or guide the experimental work

In addition, limited information of practical significance is available from structural damage during uncontrolled or accidental occurrences of sonic boom. Substantial directly relevant data are also available on blast effects on structures (ANSI S2.20 1983).

Damage Assessment for Conventional Buildings from Controlled Overflight Tests

Two types of controlled overflight tests have been carried out: (a) low magnitude (<2 psf) tests over urban areas, and (b) specialized tests at isolated sites with overpressures ranging from <2 psf up to nearly 150 psf. References for the definitive reports on these test programs are identified in Appendix A.

At the average overpressure of about 1.8 psf experienced in the carpet boom for the simulated SST overflight tests, the structural damage was very slight — limited primarily to breakage of windows in poor condition or under substantial initial pre-stress, or having large stress-risers at the edge (e.g., improperly installed glazer's points). Minor damage also occurred in the form of small plaster cracks, broken bric-a-brac, etc. Such a low but finite probability for structural damage (estimated, for example, to be of the order of 10^{-6} window panes broken

*References will be found in Appendix B, Bibliography.

per 2 psf boom) is roughly consistent with current Air Force damage claim experience. Thus, for current tactical fighter training operations, the state of the art predictions for minor damage, imprecise though it is, indicates that there will tend to be an unavoidable and continuing burden of small damage claims due to normal sonic boom environments near supersonic flight training areas.

Earlier experience from the extensive SST sonic boom overflight tests showed an average rate of number of claims settled per 10^6 boom-person exposures ranging from about 0.6 to 5 for overpressures in the range of 1.2 to 1.8 psf. More recently, NASA has experienced a small number of claims from sonic booms generated during space shuttle landing operations. A total of 37 claims have been made since 1982, mostly for minor damage (windows, etc.), with overpressures averaging about 1 psf over metropolitan areas. However, most of these damage claim data are for exposure in urban areas, so that the structures involved are not necessarily representative of those existing in the rural, remote or wilderness areas which are typical of supersonic MOA's. In such areas, buildings are likely to be older, in poorer condition, and hence more susceptible to damage.

Special overflight tests were carried out in remote areas to evaluate building or seismic responses to sonic booms with overpressures below 30 psf. In these special tests, it was found that only minor damage (hairline cracks) occurred on interior walls or ceilings of existing or specially built test structures at average overpressures of 8.2 psf, whereas major damage (falling plaster, tiles) occurred on interior walls at average overpressures of 12.2 psf. Local pressures around a residential building varied approximately ± 50 percent about the nominal free field pressure depending on the building facade position relative to the sonic boom wave front. The highest damage rates generally occurred in brittle materials subject to high tensile surface stresses.

Two controlled flight tests were also carried out with supersonic aircraft flyovers at very low altitude to generate sonic booms up to about 150 psf. Individual window specimens were specially constructed for one of these tests and up to 75 percent of the windows were broken by the highest sonic boom loads imposed (80-100 psf). Had these been existing windows in normal conditions, an even greater percentage of failure would be expected.

A number of building damage studies for sonic boom loads have also been carried out in Europe. The results have generally been comparable to U.S. test results, except where building construction differed significantly.

Laboratory Tests to Assess Sonic Boom Damage or Load

Laboratory tests of windows, walls or plate specimens subjected to simulated sonic booms have generally agreed with theoretical models. However, tests on window responses to simulated booms were not necessarily realistic when they failed to duplicate actual in-place stress conditions in which stress-risers are often located along the edges of the window pane. Laboratory tests on three-dimensional models have demonstrated the complex diffraction pattern around a building exposed to sonic booms and the complex internal acoustic response of rooms with open windows exposed to a sonic boom.

Analytical Models

Deterministic models of the classical dynamic response of simple plate or diaphragm (e.g., window) elements to sonic boom loading show very good agreement with experimental data taken under controlled conditions with idealized edge-mounting condition. Again, such models usually predict window failure at an optimistically high overpressure level, unless they are modified to include realistic representation of mounting or stress-riser conditions at the edge of the windows.

More complex, finite element, models to predict the complete response of buildings to sonic booms are possible but not very practical for routine applications. However, such models have been applied with some success for detailed analyses of severe building damage in isolated cases.

Two practical, empirically-based, statistical models have been developed to predict minor damage rates primarily for window breakage and plaster cracking (Hershey and Higgins, 1973; Wiggins, 1969). The models are only roughly validated with very limited data and differ significantly at overpressures below 30 psf. Both models agree, however, that the change in predicted failure rate is highly sensitive to changes in overpressure. Failure rate increases typically by 2 to 3 orders of magnitude for every doubling of pressure in the range of 1 to 10 psf.

Finally, very limited tests have been conducted recently to evaluate vibration (or seismic) response of archaeologically significant structures, such as Indian rock caves (Battis, 1983) and one old adobe house, but the results did not show any evidence of damage as had been suggested by the public.

Structural Damage from Uncontrolled Events

On a number of occasions, damage to buildings from unanticipated sonic booms has been reported. The type of damage has included:

- 324 damage incidents, mostly windows, reported in a 5 x 8 block wide area in a small town following two supersonic accelerating overflights by an F-100 aircraft (Arde Associates, 1959).
- Major damage ($300,000) to secondary structure of an air terminal building under construction (Ramsey, 1964).
- Extensive damage to a light metal building at an electric power station (Purcell, 1985).
- Collapse of 15th Century church building in Germany following overflight by four jet fighter aircraft (Purcell, 1985).
- Failure of a large plate glass window in a hospital operating theater (Newberry, 1967).

Seismic or Terrain Response to Sonic Booms

Peak seismic velocities induced by sonic booms fall in the range of about 0.5 to 2 in/sec for a 1 psi (144 psf) peak overpressure. Thus, for a sonic boom overpressure of 30 psf, the expected peak ground velocity would be 0.1 to 0.4 in/sec - below, but approaching, a critical velocity of 1-2 in/sec considered by the U.S. Bureau of Mines to be the threshold for building damage due to seismic excitation from blasting (Siskind, 1980a, b).

The principal theoretical study of air-coupled seismic waves excited by sonic booms has demonstrated excellent agreement with experimental data (Goforth & McDonald, 1968). An earlier theoretical study examined the "coincidence" conditions involving excitation of surface "Rayleigh" waves by a supersonic aircraft traveling at the same velocity over the ground as the local speed of these Rayleigh waves in the surface layer (Baron et al., 1966). This condition was shown, theoretically, to be capable of generating much greater seismic response than would normally occur. However, it required an unlikely close matching between the Rayleigh wave and aircraft velocity over a substantial distance, and was therefore considered improbable. However, one experimental test of seismic response to sonic boom does show possible evidence of this type of resonance condition (Espinosa and Mickey, 1968).

One controlled test on triggering of snow avalanches by sonic boom failed to demonstrate any results, apparently due to the fact that avalanche conditions were not present (Lillard et al., 1965). However, undocumented evidence does exist to the effect that sonic booms can and do trigger snow avalanches (Rathe, 1986), probably most often for avalanche areas in unstable conditions. Limited information on blast pressure loads from explosives required to trigger avalanches is also available (Gubler, 1977) to augment the extensive literature on the mechanics of snow avalanches.

At least one credible observation exists concerning an earth slide being triggered by a sonic boom (Holbrook, 1980), and concern about this problem has been expressed by the public at EIS hearings (U.S. Navy, 1985).

3.1.2 Low Frequency Response

Recent research on response of buildings to low frequency noise is available to augment the earlier basic studies on building response carried out for the SST. This more recent work provides a good experimental data base to assist in predicting the low frequency acoustic and vibration response of buildings to excitation from sonic boom and noise from static engine testing. Related work on response of buildings to low frequency rocket and aircraft noise was also carried out by NASA in the 1960's and 1970's, and by the FAA in the 1970's for Concorde operations. Analytical tools have successfully demonstrated the ability to predict the vibration response of single wall or ceiling panels and the acoustic (Helmholtz resonator) response inside a room with an open window, and driven by a sonic boom pressure pulse. More recently, analytical and experimental studies have been carried out by the U.S. Army Corps of Engineers Construction Engineering Research Laboratory (CERL). This has involved analysis (Sutherland, 1982) and extensive vibroacoustic measurements (Eldred, 1985) of a full scale room driven by a transient low frequency acoustic pulse. From these studies, preliminary models are available to predict:

- Rattle motion of loose windows (Crandall & Kurzweil, 1968), hung pictures and bric-a-brac (Sutherland, 1982).
- Noise generation by such rattle motion employing recently developed theory of impact noise generators (Richards, 1979).

- Low frequency noise transmission by external walls or windows (Sutherland, 1983).
- Internal resonant response of room volumes excited by transient (sonic boom) signals (Bressers, 1983).

Extensive research has been carried out on the acoustically-induced seismic response of the ground to low frequency noise. This work varies from early empirical studies (Sutherland, 1968) based on available experimental data from measurements taken during Saturn rocket launches to more thorough experimental and analytical studies relating to sound-induced motion of the ground (Bass, et al., 1980). The general trend of the recent work indicates that the seismic admittance of the ground to acoustic excitation (e.g., ratio of seismic ground velocity to acoustic pressure) varies significantly with frequency and exhibits spectral peaks below 100 Hz which may result in corresponding spectral peaks of seismic motion due to low frequency acoustic energy from hush houses, low altitude aircraft flyovers, or sonic booms.

3.2 Gaps in Technology

3.2.1 Structural Damage Effects

Damage Prediction - Conventional Structures

A major shortcoming with damage prediction models for low amplitude sonic booms is the lack of a well defined data base for model validation. Potentially, the most voluminous source for such data - actual damage claims made to the Air Force - is not a very satisfactory one from an engineering standpoint due to the normal inherent lack of details on sonic boom and structural response levels. Nevertheless, damage claims records, maintained for a period of about 2 years by the USAF Judge Advocate General's office (JAG), should be reviewed for relevant data. Although some statistical data on the very low probabilities of structural damage are available for failure of windows, the data are too limited to clearly resolve the substantial differences in available statistical prediction models mentioned earlier. Thus, while lacking in detail, the Air Force JAG-maintained claims records may offer a useful source of data worth evaluating to improve and extend the damage prediction models for low amplitude sonic booms to include a wider range of types of structural damage.

Data to assist in validation of prediction models for structural damage from higher sonic boom overpressures (30 psf) is provided by the extensive information on explosive blast-induced damage from weapons testing (ANSI, 1983) and from surface mining or quarry blasting (Siskind, 1980a, b). However, it has been clearly demonstrated in one test (Mayes and Edge, 1964) that, for the same peak overpressure, a sonic boom will produce a greater stress on a given structure than an explosive blast with a comparable duration. This important, theoretically expected result, can be attributed to the higher dynamic loading of the basically equal magnitude positive and negative peak pressures of the sonic boom N-wave as opposed to the weak negative pressure phase of a blast wave.

However, a single set of such data does not provide an adequate basis for full validation of this effect, and further evaluation is needed. This is particularly important in order to be able to take full advantage of the blast damage data to efficiently develop valid prediction models for structural damage from high level sonic booms.

Damage Prediction - Unconventional Structures

A major gap in the technology of structural damage prediction from sonic booms is the lack of adequate data, or supporting analytical models, covering potential damage from moderate level sonic booms to the wide range of special or unconventional structures of concern to the public in existing or proposed supersonic operations areas. These include:

- Historic natural monuments or archaeological structures
- Indian caves with ancient petroglyph drawings
- Near surface or open pit mines
- Older historic buildings (e.g., adobe)
- Wells or large open water tanks
- Radio telescope/antennae

Furthermore, just as for conventional structures, there are no guidelines for the structural damage potential to these unconventional structures from high-level sonic booms that would accompany any low level supersonic flights. While such flights are not planned for any inhabited areas containing man-made structures,

better methods should be available to the Air Force for assessing the possible damage for these unconventional structures, as well as for conventional structures, due to such low altitude supersonic flights.

Damage Prediction - Avalanche/Slide and Seismic Interaction Problems

A major gap in existing sonic boom structural damage technology is the lack of any practical model or data on the ability of some booms to trigger snow avalanches or earthslides. The available data on such events are only anecdotal, but clearly indicate, at least in the case of snow avalanches, that the phenomena have occurred. Because of the potentially catastrophic consequences of such events, a high priority effort is recommended to provide basic operational guidelines for supersonic operating areas to reduce the risk of such events to an acceptable minimum. At the present time, while the probability of triggering avalanches or earthslides is probably low, the risk cannot be adequately assessed.

Fortunately, substantial data and theoretical models are available on triggering of avalanches and slides by explosive blasts or earthquakes, respectively. These data can be brought to bear in this area. However, at least some limited additional testing with sonic booms is necessary due to the very different mechanisms on which this existing information is based.

Finally, a number of potential seismic-acoustic interaction problems are cited by the public which have not been fully resolved by past research. Thus, the studies of velocity-coincidence-coupled Rayleigh surface waves have not adequately resolved the validity of claims that have been made of foundation cracking by sonic booms, and the stated potential for seismic or combined seismic-acoustic-induced damage of water tanks or wells to sonic booms. While it is considered unlikely that these types of structures are in jeopardy due to sonic boom loads, no reliable information is available to the Air Force to demonstrate this, so that specific research on this issue is needed.

In summary, as stated well by Clarkson and Mayes in 1972,

> ". . . at the moment, there is little firm scientific data on which to predict the damage likely to be caused by supersonic overflights."

Little work has been accomplished since 1972 in this area so that new research is needed to fill these information or technology gaps.

3.2.2 Low Frequency Response

While the type of models and supporting experimental data on response of structures to low frequency acoustic energy described earlier provide a good beginning, there are still major gaps in practical knowledge in this area.

- No substantial data base exists for the magnitude of rattle vibrations and ensuing rattle noise induced by low frequency noise for a wide range of building types. These data are needed to evaluate building excitation by the transient low frequency energy in sonic booms and for the low frequency excitation by static engine testing or low-flying jet aircraft. Such a broad data base should be supported by the development of the type of deterministic and/or semi-empirical statistical response prediction models that have been extensively employed in the aerospace industry for assessing vibration environments for aerospace systems.

- Limited validation has been made of the available models for predicting outdoor to indoor low frequency sound transmission loss into buildings (e.g., including effect of leakage paths, and structural or acoustic damping). This limitation is due, in part, to the very limited low frequency data (below 100 Hz) on sound transmission into buildings. Additional data are needed to provide realistic assessments of low frequency or infrasonic sound levels inside buildings exposed to intense low frequency noise and hence support the evaluation of subjective responses to such environments.

- Measurement techniques for acquiring or specifying rattle noise levels have not been developed and evaluated in terms of subjective response models to low frequency excitation of buildings.

In the area of seismic response to low frequency noise, the current state-of-the-art is, to a large extent, oriented towards the basic sciences. It has not been translated into practical methods, needed by the Air Force, for evaluating the potential environmental impact on ground vibration-sensitive activity or human response to such vibration, caused by intense low frequency noise. Further research is called for.

3.3 Ability of Current R&D to Fill Gaps

3.3.1 Structural Damage Effects

Two R&D efforts have been identified at this time which directly relate to the area of structural damage effects from sonic boom. The first is a program, in planning by the Air Force Engineering Services Center of Tyndall Air Force Base, to collect and evaluate Air Force records on structural damage claims from sonic booms (and possibly including low altitude overflights). The results of this program would provide a valuable input to the studies needed for this NSBIT plan and, if it is not carried out, the recommended research effort outlined in the next section should be modified accordingly to include such a study.

The second activity, an extensive international, ongoing effort on snow avalanches, is much broader in scope and only indirectly related to NSBIT goals. However, intensive work in this area provides a pool of knowledgeable expertise in the field which should be tapped by any NSBIT program on sonic boom and snow avalanche hazards. It must also be recognized that sonic booms have been used in the past to trigger unstable avalanches for safety reasons (Seattle Times, 1966). Thus, a synergistic effort, in cooperation with the National Park Service or state Highway Departments, is a distinct possibility worthy of further investigation.

3.3.2 Low Frequency Response

R&D effort in two directions is currently under way which relates to this technology area. The first is the on-going research program at CERL, mentioned earlier, which has been addressing problems of low frequency response of structures. Thus, it is recommended that a first step in filling the technology gaps in this area would be to make full use of, and potentially add to, this existing research effort. Currently, the CERL program is expected to run for 2 to 3 years at a funding level of about $250,000/year. It is motivated by Army concerns for abatement of environmental impact of rattle noise from house vibration around artillery ranges and helicopter training fields. Nevertheless, the experimental facilities and type of data obtainable are directly applicable to resolving part of the problems outlined above.

However, to augment this Army-oriented effort, additional research on low frequency rattle noise and vibration is recommended to meet Air Force needs.

Secondly, research has been carried out in the United States, primarily under the sponsorship of the U.S. Army Waterways Experiment Station in Vicksburg, Mississippi, on acoustically-induced seismic response of the ground. However, the emphasis in this work is on battlefield applications and is not closely related to Air Force environmental concerns in the NSBIT Program. Thus, additional effort, building upon and utilizing applicable results from the Army research (or similar research in this area), is needed. The end product for the Air Force should provide practical guidelines for environmental analysis of potential seismic vibration problems near static test stands or from other sources of low frequency acoustic energy resulting from Air Force operations.

3.4 Required New Programs, Priorities, and Risks

Based on the technology gaps identified above and the evaluation of contributions that can be made by existing R&D effort, new R&D projects have been identified as necessary for the NSBIT Program to fulfill Air Force needs. A priority ranking from 1 (highest priority) to 4 (lowest priority) has been established for each of these programs. This ranking was developed by considering, in approximate order of importance, the following factors:

- Significance of the problem to the Air Force.
  - The Air Force needs outlined at the beginning of this section were considered in establishing this significance.
- Severity of the problem being addressed.
  - Would the damage indicated be life-threatening to humans or animals?
  - If no loss of life is involved, is a major repair cost involved?
  - Would this damage represent a serious loss or major inconvenience to someone?
- Technical knowledge already available about the problem area.
  - Are there well-documented test data or a validated theory available to predict the damage potential?
  - Are there reasonable empirical guidelines for estimating the damage potential?

The resulting programs are:

Program No.	Priority	Programs
1	1	Avalanche/Slide Triggering Evaluation
2	1	Structural Damage Criteria for Unconventional Structures
3	2	Extended Damage Prediction Models for Conventional Structures
4	3	Seismic/Acoustic Interaction
5	2	Low Frequency Structural and Seismic Response

Risks

Program 1. For this program on avalanche/slide triggering, the primary risk, discounting any unsafe testing procedures, would be that the same negative result obtained in a prior test of snow avalanche triggering (Lillard, 1965) would be obtained. After this prior test (Lillard), it was learned that weather conditions had not been appropriate for avalanches at the time of the test, so that the failure to trigger an avalanche by sonic booms was not surprising. Given the much greater knowledge about mechanics of snow avalanches and the knowledge that they have in fact been triggered by sonic booms, this risk is no longer considered serious.

Program 2. The risks involved in this program on potential damage to unconventional structures include the difficulty of adequately identifying structural failure modes and obtaining definitive data on material properties. Such data should be available for the effective development of damage prediction models for the wide range of unconventional structures involved. However, some of these risks concerning, for example, effects on adobe structures, will be minimized by applying state of the art methods now being applied routinely to masonry construction. For example, it is common practice to examine, in situ, the structural integrity of masonry buildings during earthquake resistance surveys (Lee, 1982). For other unconventional structures, such as large open water tanks or wells, variation in their existing structural integrity will present a variable that will be difficult to assess in a consistent manner. For example, wells are typically unlined below the first few feet and definitely have a finite useful life after which

they often collapse. Thus, accounting for natural causes for well collapse will tend to complicate efforts to establish the damage potential from sonic booms. Other examples of difficult damage assessment problems include historical monuments or archaeological structures. Again, acquisition of definitive data on material strength properties is a missing element in previous studies and should help to minimize risks in developing valid damage prediction models.

Program 3. The principal risk in this program on potential damage to conventional structures relates to the successful conduct of the recommended field test. For this test, it is proposed that structural response and/or damage be measured on test buildings (desirably expendable existing structures and not newly-built ones) exposed to sonic booms from low-level flights. For the analytical portion of Program 3, the only significant risk envisioned will involve development of adequate statistical data on estimated in situ response levels for the wide range of structures to be considered. However, new sources of information, such as the extensive Bureau of Mines test data and previous explosive blast response data on buildings not previously utilized to any significant degree on sonic boom/structural damage studies, will help to minimize this risk.

Program 4. Relatively long-term seismic measurements are planned for this program on seismic/acoustic interaction. However, these data will be acquired in normal supersonic operating areas and will not require dedicated flights. Thus, the principal risk is associated with the unavoidable lack of control on this sonic boom excitation. Accompanying this is the associated risk that the unique and potentially infrequent coincidence required between the seismic wave velocity and trace velocity of the sonic boom pattern may not be observable in such a program. On the positive side, however, are the observations that: (1) the existence and theoretical foundation for this seismic/acoustic interaction has been confirmed experimentally (Espinosa, et al., 1968), and (2) a negative result would still be useful as an indirect measure of the very low probability of such conditions occurring.

Program 5. For this program on low frequency structural and seismic response, no significant risk is envisioned since a substantial experimental data base and basic analytical models are already available for evaluation of both phenomena to support the development of valid prediction models.

4.0 RECOMMENDED PROGRAMS

In this section, detailed descriptions are provided for the recommended programs defined earlier – four on structural damage effects of sonic boom, and one on structural and seismic response to low frequency noise.

4.1 Program No. 1: Avalanche/Slide Triggering by Sonic Boom

4.1.1 Objectives

Develop practical methods of predicting the probabilities of triggering either snow avalanches or earth slides by sonic booms.

4.1.2 Scope

The study should provide specific guidelines for ascertaining the risks of triggering avalanches or slides by operating particular aircraft within defined operational limits over topography which includes relatively steeply sloping ground having snow or soil cover. Provisions will be included to factor the physical ground cover conditions appropriate to the day and time of the operation into the prediction models which form the basis of the guidelines. The models will be based on a critical review and analysis of existing data on avalanches and earth slides supported by a field test program involving generation of sonic booms.

4.1.3 Technical Requirements

The four phases involved in this program are first briefly summarized and then described in more detail.

Summary

Phase I: Review and Risk Assessment

Review existing general information applicable to acoustic pulse loading of snow and soil slopes and resultant avalanche or slides, and review available site-specific information for supersonic operating area to allow preliminary qualitative risk assessment and prioritizing of test sites.

Phase II: Correlate Available Models

Correlate earthquake loading damage to soil slopes and explosive triggering of snow slopes with sonic boom loading signatures and evaluate differences in triggering loads, and develop preliminary avalanche slide triggering model.

Phase III: Experimental Testing

For snow avalanches; establish a high-risk location for sonic boom-induced avalanches based on the data acquired in Phase I and Phase II and conduct a short series of controlled tests to validate the model. Repeat the same activity for a soil slide area.

Phase IV: Prediction Models

Based on the results of the preceding three phases, develop practical prediction tools, usable by flight operations managers, for assessing the risk of triggering snow avalanches or earth slides as a function of local weather and geology and type of aircraft operations (i.e., altitude and speed).

Detailed Requirements

Phase I: Review and Risk Assessment

The mechanics of soil and snow slipping are reasonably well established and documented. Less well understood is the interaction of sonic boom over-pressures with the triggering of such slips although several undocumented incidents have been reported. In this phase an exhaustive review of the available information will be made with the objective of developing a preliminary prediction model for estimating the probability and approximate conditions required to trigger snow avalanches or earth slides by sonic booms. This review would include avalanche mechanics and triggering by explosive blasts, soil slipping under dynamic (e.g., earthquake or other vibratory) loads, and a definition of comparable forcing functions for sonic boom signatures.

Armed with this preliminary information, the data on weather, geology, and terrain of supersonic operating areas would be reviewed to provide an initial validation ranking of these special operating areas in terms of relative risk of avalanches or slides being triggered by sonic booms. This site-specific information will be available from geological survey maps to identify areas where slope would be greater than critical values based on site-specific geomechanics (surface conditions) and changes in ground cover, and from contacts with local experts such as forest rangers or highway maintenance engineers. The objective would be to: (1) identify candidate test sites, and

(2) put into initial perspective the risk for such events in areas of primary concern to the Air Force.

Phase II: Correlate Available Models

This phase would involve refinement of the snow avalanche and soil slipping models defined in Phase I to incorporate sonic boom excitation.

First, mathematical models would be developed from those identified in Phase I from the known triggering effects (earthquakes or explosive blasts) in terms that can be related to sonic boom loads (e.g., equivalent overpressures). Then the sonic boom signature would be incorporated to simulate the sonic boom triggering effect. The effect would be a preliminary model for predicting avalanche or earth slide triggering by sonic booms. This model would then be compared with available (anecdotal) information on actual avalanche or slide triggering by sonic boom to provide an initial crude validation. This preliminary model would also be applied to the previously collected site-specific data base relative to avalanche or slide conditions in existing supersonic operating areas. This step would be designed to refine, if necessary, a test site selection for full-scale field testing. A preliminary plan for this testing would also be generated at the end of this phase.

Phase III: Experimental Test

To validate these preliminary prediction models and thereby cover the range of likely operating conditions and snow or soil parameters, an experimental program is envisaged. This will involve:

- Final selection of a test site.
- Preparation of a Final Test Plan.
- Conduct of Preliminary Pilot Test to confirm test procedures.
- Conduct of expanded Test Program.
- Analysis of data.

Test Site Selection

It is anticipated that locations with a high probability for triggering of avalanche or earth slides by sonic booms may not exist within current, conveniently accessible, supersonic operating areas. Alternate locations would then be considered as sites for possible further review. For example, the San Juan Mountains in

Colorado, perhaps the most avalanche-prone area in the U.S., have been under intensive study for many years for avalanche hazards (Armstrong, et al., 1976, 1983, 1984). If safe conditions permit, this alternate site may provide a more suitable test location. The general area is located about 170 miles west-southwest of Colorado Springs, near the town of Silverton, Colorado, and lies in a mountainous area on the Continental Divide with 14 peaks exceeding 14,000 ft.

Test Plan

Following selection of general test sites for evaluating triggering of avalanches or slides, an experimental test plan would be drawn up for review by the Air Force. This plan would include:

- Methods of observation. Visual inspection, preferably from an aircraft or helicopter, is the simplest recommended procedure for detecting occurrence of snow avalanches in very remote areas. Such visual methods could also be supported by seismographic measurements if it were found necessary (Gubler, 1977).

- Methods of sonic boom measurement. The type of portable, unattended instruments recently employed in sonic boom monitoring in the Reserve MOA could be employed.

- Supersonic aircraft flight path. Although methods have been developed employing linear shaped explosive charges to simulate sonic boom pressure signatures for structural testing (Harper, et al., 1970), the area influenced in a snow bank by implanted or surface explosive charges is limited to less than 100 m (Gubler, 1977). Thus, the much larger area covered by the carpet pattern of a real sonic boom from a level, supersonic, flight path could not be accurately simulated. Therefore, it is not considered practical to employ any substitute for a sonic boom to accurately assess its potential for triggering an avalanche or earth slide.

- Logistics plan. Specific procedures to transport test personnel, set up instrumentation, establish any intercommunication required with Air Force operations people, and maintain safe conditions, would be defined.

- Coordination plan. If any other Government agency participated in (or co-sponsored) the tests, specific arrangements for intercoordination between all parties would be required.

Pilot Test (Avalanche Triggering)

A preliminary test would be conducted using a limited scenario of two or three dedicated supersonic overflights carried out within 1 day. (The test day would be carefully chosen for optimum weather conditions.) Test procedures would be reviewed and modified as necessary for an expanded test program.

Expanded Test Program

For a specified period of time (estimated to be 2 to 4 weeks) during the avalanche season, one or more sonic boom patterns would be laid down on the test site for at least 50 percent of the observation days. The supersonic flights would be planned to cover as wide a range of sonic boom overpressures as practical. No sonic booms would occur on the remaining 50 percent of the observation days.

Data Analysis

Frequency and location of all snow avalanches occurring in the test area during the entire test period would be recorded and the number and extent for "no boom" days compared to those for "boom" days to provide the basis for statistical evaluation of the effectiveness of sonic booms for triggering snow avalanches.

In addition, sonic boom overpressures recorded during the tests would be used to compare predictions of avalanche triggering, based on the previously constructed model, to the actual observations. The prediction model would then be adjusted accordingly.

The preceding has emphasized research on triggering of snow avalanches — primarily because it is anticipated that they are more likely than earth slides to be triggered by sonic boom. However, if the results of the Phase I and Phase II effort on earth slides indicate that testing is justified, an experimental program similar to that outlined for avalanches would be conducted. To provide a basis for a conservative estimate of program costs, it was assumed that such a test program on triggering of soil slides would also be carried out at one site.

Phase IV: Prediction Model

Based on the analytical tools available from the previous research (reviewed in Phase I) and the new tools developed in Phase II and validated in Phase III, a method will be developed to predict triggering of snow or avalanches or soil slides due to supersonic flights over typical sloping terrain. This development will involve the following elements:

Establish the range of material mechanics encountered in typical supersonic operating areas. Physical characteristics of the snow and soils which are critical relative to avalanche or slide risk, such as approximate density, soil type, moisture content, and deposition history, will be identified and simple methods established for documenting these parameters. These documentation methods will normally depend on data already available from sources such as U.S. Coast and Geodetic Survey maps showing contours and, hence, slopes; geological surveys on record; aerial photographs; and historical data on avalanches or slides available from park or highway personnel. These data sources will be used to identify areas where slide-prone slopes and soil types, such as loosely constituted soil deposition on steep slopes, or avalanche-prone areas, exist within a supersonic operating area. The avalanche hazard would normally exist only during the winter so that the documentation, in this case, would include a review of historical records of pertinent climatic conditions (i.e., snowfall, temperature, etc). This sort of mapping of potential slide or avalanche hazard areas would only need to be done once for any given supersonic operating area.

For any critical areas (such as those adjacent to roads or any places inhabited permanently or on a transient basis) where the hazard documentation is inadequate to properly assess the risk based on available data sources, procedures should be defined for carrying out field inspections or on-site testing to permit verifying classification (or declassification) of such areas as hazardous relative to avalanche or soil slide triggering by sonic booms. <u>However, execution of such special field testing has not been included in costing this program – only the procedures would be defined</u>. Furthermore, this level of refinement would only be justified if the prior phases had indicated that such an effort was warranted based on evidence of a significant probability of avalanches or slides actually being triggered by sonic booms in specific supersonic operating areas.

Next, the preliminary avalanche or slide prediction model developed in Phase II would be refined, as necessary, based on the experimental results of Phase III, and a final prediction model established. This model would then be correlated with the "hazard mapping" data to provide a practical set of operational guidelines for use by airspace managers of supersonic operating areas. These guidelines would be designed to allow planning of supersonic operations for any given time period (potentially on a day-to-day basis in the winter for avalanche-prone areas) in such a way as to reduce the hazard of triggering avalanches or slides by sonic boom to an acceptable minimum. In its simplest form, such a guideline might take the form currently used in Switzerland whereby supersonic flights of Swiss military aircraft are cancelled when "medium to acute danger of avalanches is announced on the radio" (Rathe, 1986) – a routine part of regular reports of snow conditions for the benefit and safety of recreational skiers, especially those skiing in high mountain areas (Gubler, 1977).

Finally, a procedure would be outlined by which the effectiveness or validity of these operational guidelines for potential constraint on supersonic operations could be reviewed periodically by a feedback process and adjusted as required.

4.1.4 Schedule of Deliverables

The estimated schedule for the four-phase program is as follows:

		Years					
		0	1	2	3	4	5
Phase I	Review & Risk Assessment	—					
Phase II	Correlate Available Models	—	—				
Phase III	Experimental Testing		—	—	—		
Phase IV	Prediction Models				—	—	

The deliverables would consist of:

Phase I: <u>Interim Report</u> - A summary of the Literature and Information Review and presentation of the initial risk assessment.

Phase II: <u>Interim Report</u> - (1) Outline of preliminary prediction model, and (2) test plan for execution of Phase III.

Phase III: (1) Final Test Plan, and (2) a Test Report providing definitive results of the experimental test program.

Phase IV: Final Report in two parts. Volume 1 would be a complete report summarizing the results of Phases I through III and would present a final prediction model for the relative avalanche/slide triggering potential of sonic booms. Volume 2 would contain a condensed version of the technical background in Volume 1 and would present a specific set of operational guidelines to be used by airspace managers for controlling supersonic flight activity in any areas involving significant avalanche/slide hazards.

4.1.5 Estimated Resources and Supporting Facility Requirements

	Costs ($1,000)			
	Phase			
	I	II	III	IV
Principal Investigator	30	50	60	30
Research Engineer	20	60	120	40
Technician/Typist	5	10	60	10
Logistics Support			30	
Expendable Supplies			25	3
Travel	—	5	10	2
	55	125	305	85
TOTAL		$570,000		

Supporting Facilities

A maximum of approximately 25 dedicated supersonic sorties (each consisting of two passbys, one in each direction, on each of 25 days) by fighter aircraft is estimated as a maximum supporting requirement by the Air Force. It is expected, however, that should results of the first few flights unequivocally demonstrate the triggering potential of sonic booms, the remainder of the flights might be cancelled. No other supporting facility requirements are envisioned at this point. Provision for contractor-supplied aerial inspection of avalanche or slide areas has been included in the logistics support.

4.2 Program No. 2: Structural Damage Criteria for Unconventional Structures

4.2.1 Objective

Develop prediction criteria for probability of damage to a variety of unconventional structures in supersonic operating areas. The structures include

adobe buildings, archaeological objects, historic monuments, storage tanks, radio-astronomy antennae, and water wells.

4.2.2 Scope

The methods developed should provide a technique for assessing the degree of damage to each of the types of unconventional structures identified above likely to result from specified sonic boom overpressures, and should provide guidelines for safe operations over these unconventional structures. The program would be primarily analytical but would include a limited experimental effort to demonstrate a portion of the more critical results.

4.2.3 Technical Requirements

The proposed program reflects the variations in established technology for determining dynamic load response. Whereas well-developed mathematical modeling techniques exist for the analysis of elevated storage tanks and radio-astronomy antennae, much less work has been done on some of the other unconventional structures listed and hence more fundamental investigations will be necessary in these cases.

The several subprograms are listed below in summary form in decreasing order of importance.

Summary

Wells

A three-phase subprogram is proposed involving: (I) a review of the soil mechanics of well structures and their vulnerability to seismic waves, (II) an analysis of the response to sonic boom-induced waves, and (III) establishment of relationships between seismic damage threshold and seismic environment of the supersonic operation.

Storage Tanks

A three-phase subprogram is proposed involving: (I) a review of existing earthquake and blast response models for storage tanks, (II) translation and application of these models to a preliminary prediction model to sonic boom loading, and (III) a limited experimental demonstration program and development of a final damage prediction model.

Adobe Buildings

A four-phase subprogram is proposed involving: (I) a review of the prevalence, age, condition, etc., of adobe structures in supersonic operating areas, (II) an extension of the data base for material and structural properties of adobe, (III) an analysis and testing of the response to seismic and acoustic sonic boom loadings, and (IV) establishment of damage prediction criteria.

Monuments and Archaeological Structures (Indian carvings, rock caves, etc.)

A five-phase subprogram is projected involving: (I) establishment of the type, frequency, and historical ranking of importance of monuments in supersonic operating areas, (II) analytical study of dynamic response and stability of monuments to natural phenomena (earthquakes and windloads), (III) laboratory testing of available (or representative) material samples from monuments (or prototypes), (IV) evaluation of past failures, and (V) finalization of guidelines for the likelihood and degree of damage to monuments expected from sonic booms.

Radio Telescope Antennae

A four-phase subprogram is proposed involving: (I) establishment of operational limitations on dynamic response of the antenna, (II) definition of critical sonic boom loading (acoustic or seismic), (III) analysis of anticipated response and comparison with operational criteria, and (IV) establishment of criteria for possible constraints on supersonic operations near such antennae.

Detailed requirements for each of these subprograms are specified below.

4.2.3.1 Wells

Phase I: Wells

This phase establishes the materials in which typical wells are sunk, the basic geotechnical properties of these materials and the likelihood that relatively small seismic waves will cause collapse of the wells. Local well boring records and recognized geotechnical analysis techniques will suffice for this phase. Useful information on these matters could probably be obtained from local well-drilling companies. It should be noted that a water well, especially an unlined well, has a finite lifetime, often collapsing from normal causes.

The effort in this phase would include a review of water well configurations and locations in supersonic operating areas and an evaluation of the dynamic response of these well structures to existing dynamic loads from earthquakes.

Phase II: Wells

Analyses would be carried out to determine the stresses induced at the free face of the well wall as a result of sonic boom-induced body waves being transmitted through the soil medium. This would include setting up a mathematical model of the well in the surrounding soil and carrying out a numerical analysis of the stress response to sonic boom-induced seismic waves.

Phase III: Wells

Based on the known failure stresses of typical soils and rocks, and the results of Phase II, criteria will be developed to relate the likelihood of these stresses being exceeded by sonic boom-induced seismic vibrations. Only wells lined with masonry or not lined would be considered since any wells fully lined with a metal casing are quite unlikely to suffer damage from what is already known to be relatively low seismic loads. Finally, the overall results would be used to produce and document damage prediction criteria for wells.

4.2.3.2 Storage Tanks

Phase I: Storage Tanks

This phase would involve a review of the well established mathematical modeling techniques available for predicting the response of ground and tower mounted liquid storage tanks to earthquake ground shaking and a review of the response to blast loads of various forms of storage tanks. It would include a review of recent work by Haroun (Haroun, 1983) and others on dynamic response of liquid storage tanks, and a review of their response to blast loading (Norris et al., 1959).

Phase II: Storage Tanks

Phase II will involve a determination of the damage threshold to tanks arising from ground shaking or acoustic loading induced by sonic boom. This will include a mathematical analysis, using potentially finite element techniques if warranted. The effort will involve setting up mathematical models of typical above-ground or ground level tanks and applying seismic or acoustic excitation input to determine responses (accelerations, velocities, displacements) and hence

stress levels. A limited experimental (demonstration) program would also be carried out on two typical tanks, one tower-mounted and one in the ground, both exposed to sonic boom loads. This program would be restricted to a single supersonic sortie, with two overflights (one in each of two opposite directions) in 1 day over each of the two types of tanks. Instrumentation would consist of a limited number of accelerometers and/or strain gauges plus one acoustic sensor, all capable of being recorded on one portable multitrack recorder.

Phase III: Storage Tanks

In the final phase, criteria will be established for the prediction of sonic boom-induced response including the probability of not causing damage to storage tanks by stressing them only within the elastic range. The end result will be a definitive damage prediction model for stress response of liquid storage tanks to sonic boom. The model will include conservative provisions for local stress risers or weak joints that may be present in old tanks.

4.2.3.3 Adobe Buildings

Phase I: Adobe Buildings

Phase I will establish the range of adobe structures likely to be found in SOAs, their age and condition and the basic strength of the material. This will involve some in situ materials testing as well as laboratory measurement. This review of the prevalence, age and condition of adobe buildings in SOAs will assist in prioritizing sites and representative structures suitable for further investigation. In addition, available information on the range of material strength of adobe will be assessed. Plans for in situ testing of basic material properties of sample adobe will be prepared, based on the use of the type of techniques similar to those utilized for earthquake resistance surveys and testing of masonry construction (Lee, 1982).

Phase II: Adobe Buildings

This phase will involve an extension of the data base for material and structural properties of adobe. The data base will be extended by applying the available techniques for fired clay brick and concrete block buildings to adobe structures to assess their resistance to dynamic loads. This data extension will prove a basis for predicting sonic boom-induced damage to adobe buildings. In support of this phase, the limited field program planned in Phase I of modified in

situ (material property) testing or analysis techniques appropriate to adobe will be carried out on a sample of 10 to 20 adobe structures of varying ages. This field testing of material properties will be backed up by a limited amount of laboratory testing (i.e., static load tests of adobe specimens).

Phase III: Adobe Buildings

The first part of this phase will include an analysis of the response to seismic and acoustic sonic boom loadings. Methods similar to those used to predict (a) earthquake damage, and (b) blast damage will be applied to the analysis of the response of adobe buildings to sonic boom induced loads. The effort will include a review of computer-based analysis methods developed for earthquake and blast loading of buildings, and application of similar techniques to adobe buildings. In the second part, verificaton tests using sonic boom loading will be conducted on two adobe buildings, one in current use and good repair, and the second in poor repair. It is anticipated that, for this sonic boom loading test, it will be possible to employ, on a noninterference basis, targets of opportunity from normal supersonic operations, probably out of Luke AFB. Therefore, no added cost for dedicated supersonic flights are included for these tests. Instrumentation provisions will be similar to those identified for the tests on tanks.

Phase IV: Adobe Buildings

Finally, damage prediction criteria will be drawn up in terms of the probability of a given supersonic operation causing acceptable stress levels in adobe to be exceeded. This will involve using defined sonic boom loads to determine whether sonic boom of a given magnitude will cause unacceptable damage to adobe construction.

4.2.3.4 Monuments and Archaeological Structures (Carvings and Indian Rock Caves)

Phase I: Monuments, etc.

This phase will establish the type and frequency of monuments in SOAs and will attempt to gather information on ranking of historical importance. Also, a calibration of the present condition of the most prevalent and historically significant objects will be undertaken in at least two supersonic operating areas.

Phase II: Monuments, etc.

In this phase, an analysis of the response to existing dynamic loads (earthquakes or high winds) and stability of typical monuments will be made. Particular emphasis will be placed on investigating the behavior of such structures in earthquakes and probable failure modes will be established. This analysis will provide a basis for predicting damage to existing dynamic environments and the resulting damage prediction will be correlated with available actual damage reports for at least two sites. The effort will involve a review of mechanics of monuments and archaeological structures, in particular their stability under dynamic loads, and correlation of mechanics of failure with actual damage reports.

Phase III: Monuments, etc.

Although it is expected that the range of materials found in natural or man-made monuments or archaeological structures will vary widely, as will the degree of natural deterioration of the older ones in particular, some testing of the materials of construction is envisaged in order to place bounds of the expected material properties. This program will involve selection of appropriate pieces – possibly parts already fractured from the main monument – for testing to establish tensile and compressive strength. Thus, the effort will involve selection of typical monuments (from the high priority sites established in Phase I) suitable for testing. These may include abandoned cliff dwellings or similar historic dwellings, and Indian rock caves. On-site or laboratory testing of available specimens from these typical monuments would be carried out to establish engineering material properties.

Phase IV: Monuments, etc.

On the basis of the preceding phases, case studies of available documented past failures will be made in order to verify the damage with likely applied load intensity. This will involve the identification of documented past failures for case study. (Natural causes of increased fragility include poor structural design, low grade material properties, or poor condition). This information will be used to attempt to verify mathematical models in the light of past failures.

Phase V: Monuments, etc.

Finally, guidelines regarding the likelihood of monuments or archaeological structures suffering damage as a result of sonic boom loading will be developed. In

view of the very large variations expected in the quality and condition of these types of structures, it is anticipated that these guidelines can only be in the form of broadband probabilities. The effort will include consideration of the range of applicability of the particular material samples examined to the whole population of such structures. In other words, an effort will be made to define just how widely these limited results can be applied. The result will be the development, through a limited effort, of broadband sonic boom damage criteria for both historical and archaeological structures and criteria for potential constraints on supersonic operations over such structures. These would probably consist primarily of altitude limitations.

4.2.3.5 Radio-Astronomy Antennae

Phase I: Antennae

This program is applicable to disturbance, by sonic booms, of radio-astronomy antennae located near the Sells MOA but would provide generic results applicable to any other area with similar vibration-sensitive frame structures. The first phase includes establishment of operational limitations on dynamic motion of these structures, in particular their allowable amplitude of vibrations and direction pointing accuracy. Behavior in high winds will also be reviewed.

Phase II: Antennae

This phase will involve selection of dynamic loads arising from sonic booms, either acoustic or seismic excitation, the choice of worst-case conditions being influenced by the known dynamic characteristics of the antennae.

Phase III: Antennae

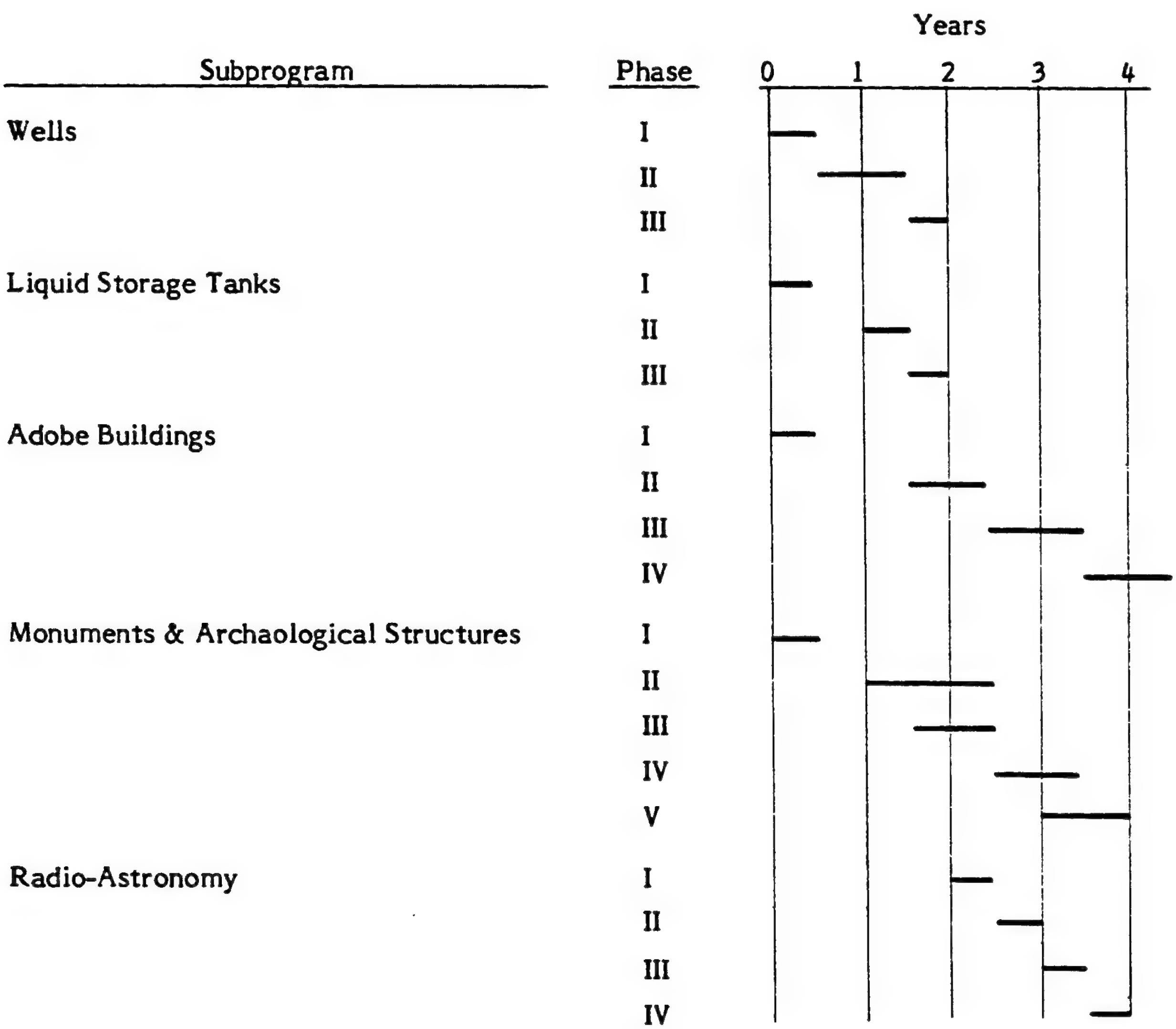
Response analyses will be undertaken using computer-based mathematical modeling techniques. The expected maximum amplitude and other vibratory characteristics of the antenna as a result of sonic boom loading will be determined. The state of the art in this area of dynamic analysis of frame structures is such that experimental verification is not considered necessary (Shepherd, 1986). Furthermore, it is anticipated that dynamic analyses will already have been carried out on these structures during their design, and these will assist in execution of the additional analyses called for here.

Phase IV: Antennae

This last phase will establish operational criteria for constraints on supersonic flights consistent with limitations to avoid unacceptable disturbances to these vibration-sensitive antennae. This will involve a sensitivity analysis to provide a data base on which to establish the reponse of standard antennae to anticipated supersonic operations and define the possibility of operational effectiveness of the antennae being impaired by sufficiently high sonic boom signatures.

4.2.4 Schedule and Deliverables

The following 4-year schedule is anticipated for completion of the five basic subprograms within this overall program on unconventional structures:



The deliverables would have the following common format for all five subprograms:

- Preliminary Review and Risk Assessments. A preliminary analysis of the technical background on the problem area, including a review of the literature or any significant unpublished data or information, a preliminary definition of specific supersonic operating areas where the problem may be significant and a preliminary qualitative estimate of the possibility that the type of damage under consideration could occur. These documents would provide a basic review point for the Air Force for approving further continuation of each subprogram. The reports would normally be provided at the end of Phase I of each subprogram.

- Interim Technical Reports. These would provide interim technical results following development of initial damage prediction models and upon completion of any field materials or sonic boom testing. Test plans for the latter limited sonic boom tests (where applicable) would be submitted separately for Air Force approval prior to conduct of the tests.

- Final Technical Reports. The final reports for each subprogram would provide the final damage prediction model and summarize all of the technical effort carried out on the study and would outline the basis for practical damage prediction models or any operational constraints (if any) on supersonic flights that may develop out of the studies. Any such constraints are likely to consist, at least, of recommended minimum altitudes for supersonic flights over sensitive unconventional structures.

- Summary Report. This single report would briefly summarize the technical background in each of the subprograms and clearly define the practical guidelines or criteria for damage estimates usable by planners or guidelines, if found necessary, for operational constraints on supersonic flights over sensitive unconventional structures.

4.2.5 Estimated Resources and Supporting Facility Requirements

Estimated costs for each part of this program are defined below:

	Costs ($1,000) Subprogram				
	Wells	Tanks	Adobe	Monuments	Antennae
Principal Investigator	25	35	30	32	25
Research Engineer	55	75	70	90	55
Technician/Typist	6	26	27	30	9
Logistics Support	--	5	5	5	--
Expendable Supplies	2	5	5	5	5
Travel	1	6	6	6	1
Subtotals	89	142	143	168	95
Overall Total			$637,000		

4.3 Program No. 3: Extended Damage Prediction Models for Conventional Buildings

4.3.1 Objective

Develop practical methods for predicting damage, especially major damage, to an extended range of conventional structural elements.

4.3.2 Scope

The program will define the expected type, severity and approximate probability of damage, principally major damage to an extended range of conventional structural elements, in addition to windows, due to sonic boom loads. The program would consist of a thorough evaluation of existing empirical damage data from blast and sonic boom tests, development of a statistical damage prediction model with a wider range of application than previous models, and a carefully targeted test program to acquire critically needed additional data in support of the final prediction method. The final product would consist of a general manual for use by the Air Force planners or claims adjusters, providing statistical prediction models for minor and major damage to a wide spectrum of conventional building components.

4.3.3 Technical Requirements

The program would be conducted in the following four phases.

Phase I: Review of Existing Data Applicable to Sonic Boom Damage Predictions with Emphasis on Major Damage

Phase II: Development of Preliminary Damage Prediction Models

Phase III: Test Program to Acquire Data on Major Damage

Phase IV: Development of Final Damage Prediction Model

The detailed design requirements for each of the four phases are defined as follows:

Phase I: Review Existing Damage Data

Existing data and prediction models from earlier SST studies for minor damage to conventional structures from sonic boom emphasizes window damage. This information will be extended to minor damage of other types of structure by (1) extraction of the limited response or damage data on other types of structure from the previous SST studies, and (2) correlation of these data with the extensive data on minor damage of a wider range of types of structural elements from surface mining and quarry blasting studies.

Information on major building damage from sonic booms is generally limited to qualitative observations from a few accidents. However, considerable data exist on structural response and relatively major damage from conventional and nuclear blast studies.

During this phase, a comprehensive review and analysis of such data will be conducted to determine their applicability to extend damage prediction models to a wider spectrum of types of structural elements and levels of damage. The effort will therefore include a thorough review of available and applicable data on response and damage to buildings from impulsive loadings – sonic booms and blasts – with particular attention directed toward:

- Identifying the most probable failure modes (beyond window breakage, plaster cracking, bric-a-brac failures, etc.) as impulsive pressures are increased in magnitude.
- Identifying data in which building response is correlated with damage type (failure mode) and severity.
- Identifying data in which building response is correlated with loading pressure time-history, with or without accompanying damage.

The data will then be summarized in terms of damage type and severity vs overpressure for each type of impulsive pressure loading.

Phase II: Development of Preliminary Damage Prediction Models

This phase will have two objectives:

1) Develop statistical damage prediction models on the basis of available empirical data from Phase I.

2) Identify further test data required to refine the models for practical use.

Statistical Damage Prediction Model

To meet the first objective, maximum use should be made, in the manner outlined below, of available empirical data on structural response and damage. This empirical approach, anchored to existing measured data, is intended to eliminate the uncertainties associated with depending totally on theoretical structural response predictions. The approach will involve development of a preliminary statistical damage model for the most frequent damage types (failure modes) determined in Phase I. Then statistical damage prediction models will be developed on the basis of the simplified adjustments and extrapolations of empirical structural response and damage data, illustrated in very simplified form in Figure 4-1. The figure illustrates the concept of how measured response and damage data from blast loads on a given structural element, such as a wall or roof structure, will be used to estimate the corresponding response and damage due to sonic boom loads, for the same structural element. The overall procedure illustrated is based on the following principles or assumptions.

- Structural damage from realistic sonic boom loads (2 - 150 psf) is most likely to occur as a result of failure of brittle materials.

- Load-stress response curves of such materials tend to be roughly linear up to the point of failure as compared to more non-linear load-response curves of non-brittle (elastic-plastic) materials.

- Given the tendency for approximately linear load-response behavior of the more critical (brittle) materials, magnitudes of responses to various loads will vary in approximate direct proportion to the effective magnitude of the load.

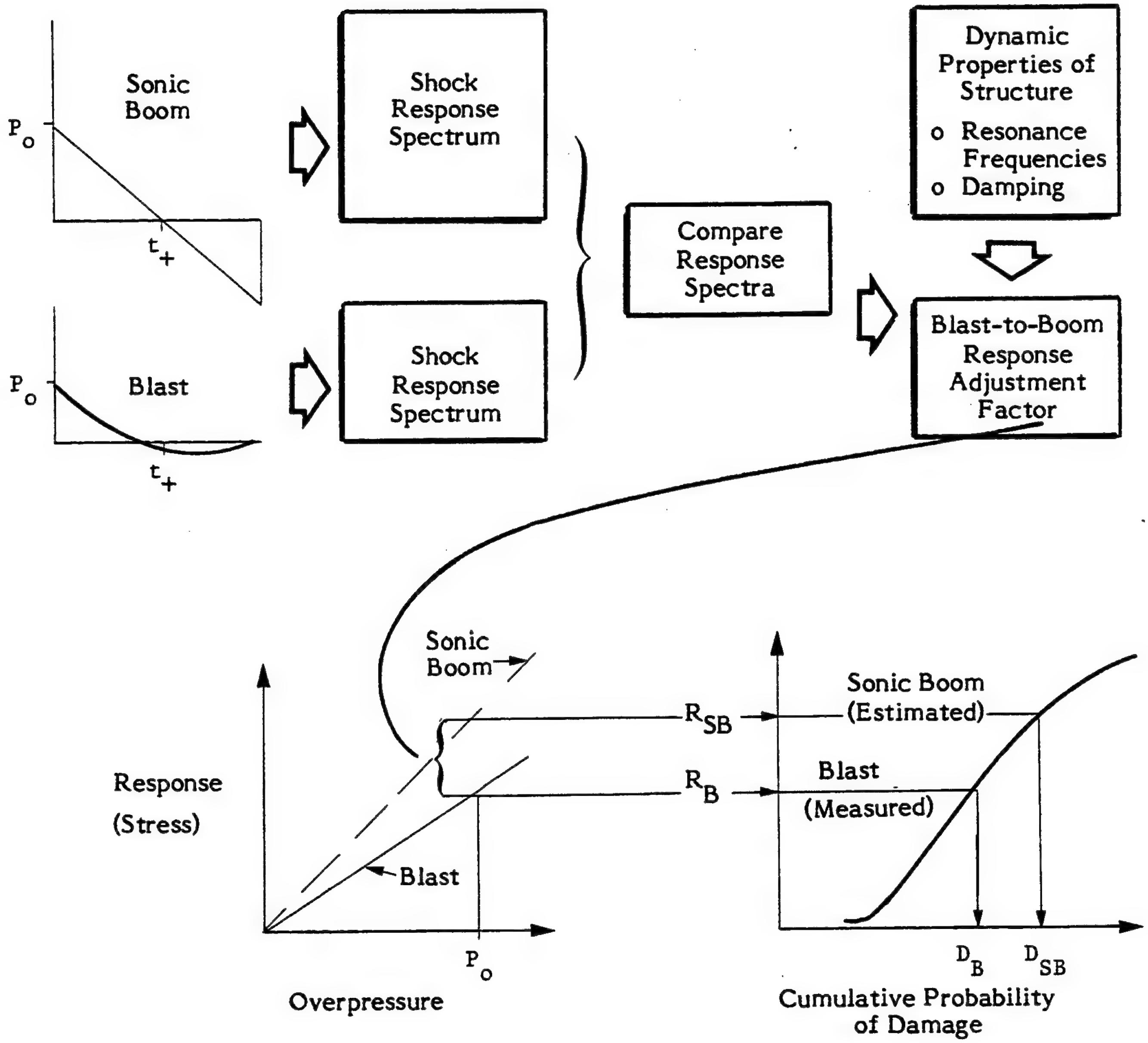


Figure 4-1. Conceptual Illustration of How Measured Blast Response and Blast Damage Probability Data for a Given Structure Will be Used to Estimate Response and Damage Probability from Sonic Booms for the Same Structure Based on Comparison of Shock Response Spectra for the Two Different Types of Excitation. (The procedure is not restricted to the case illustrated where the peak overpressure P_o and positive phase duration t_+ are comparable.)

- Effective magnitude of different types of impulsive loads, such as blast and sonic boom, can be expressed in terms of their relative shock response spectra.
- An equal magnitude (or probability) of damage of a given structural element is expected for equal response magnitude, regardless of the source of the (impulsive) load.

Therefore, stress response and corresponding statistical data on failure or damage to buildings or building components, as a result of blast loads, will be used to estimate response to sonic booms by evaluating the difference in effective magnitude of the two different types of impulsive loads.

The concept is analytical in principle but will ultimately rely upon measured load-response-damage data, especially statistical forms, for its full application.

Furthermore, applying the same principles of linear load-response relationships, the extensive measured response data on buildings actually due to low amplitude sonic boom loads can be extrapolated to predict response to higher level sonic booms, up to the point of predicted probability of building component failure.

In summary, blast damage or sonic boom response data will be used to provide statistical estimates of a wide range of types and levels of potential building damage from sonic booms.

Identification of Additional Test Data Required

In conjunction with the development of the preliminary model just outlined, additional test data required for practical damage predictions will be identified and a preliminary test plan prepared. Required data is expected to fall in the following categories:

1. Major damage type and severity
2. Structural response associated with the damage
3. Statistical strength data including variations in construction type, geometry, states of repair, and material strength.

Phase III Test Program to Acquire Data on Major Damage

As pointed out in Appendix A, the highest sonic boom overpressures to which complete buildings have been subjected in any controlled test is about 50 psf (Nixon

et al., 1968). Thus, new data are considered necessary to more clearly establish the actual nature of potential structural damage to overpressures in the range of 50 to 150 psf.

While there is no reason to expect that exposure of structures to such environments is planned, it is considered necessary that the Air Force document more accurately the potential building damage consequences of very low altitude supersonic flights to aid in planning feasible locations for flight training activity. Such training may involve low altitude terrain-following operations by advanced technology aircraft such as the Advanced Tactical Fighter or the FB-111.

While very rough estimates of potential structural damage for these higher overpressures would be possible by extrapolation of blast damage data as outlined earlier, the very different time history of low altitude sonic boom signatures (see Appendix A) would make such an extrapolation very suspect. Furthermore, simulation of these high sonic boom overpressures with special linear shaped explosives does not, at this point, appear feasible. Thus, no substitute for conducting actual low altitude tests in realistic test buildings is feasible for acquiring the data required to fill the information gap identified above.

Test Program Plan

Based on an approved version of the preliminary test plan developed in Phase II, a detailed test program plan would be developed to acquire the necessary data. Test plan elements should include:

1. Test site - an unpopulated area close to an Air Force base for supersonic aircraft would be essential.

2. Overflight trajectory - varying altitudes down to 100 ft AGL and uniform supersonic speed on relatively short horizontal runs would be used.

3. Test structures. It is recommended that a representative collection of 3 or 4 different building types be employed, preferably existing buildings in average condition, purchased and moved on-site or equivalent structures created from intact reassembled sections of demolished buildings. The objective would be to provide some degree of realism as to building condition.

4. Acoustic and structural response monitoring instrumentation including pressure, acceleration, strain and displacement measurements.

5. A complete logistics, communication and safety plan.

6. Limited laboratory type or in situ tests to establish structural strength or mechanical property data would also be conducted.

Conduct Test

Only a limited number of overflight tests should be required to validate models for major damge types and associated structural responses. It is not anticipated that such tests would provide very much statistical response data. Statistical inputs to a prediction models would be obtained more practically through the broader range of responses and damage data collected in Phases I and II. These statistical damage data would be augmented as necessary with published statistical data on material properties so that the limited damage data obtained in the field test program, combined with the in situ materials or static strength data, could be expanded to include a wide range of statistical variation in material properties and failure modes.

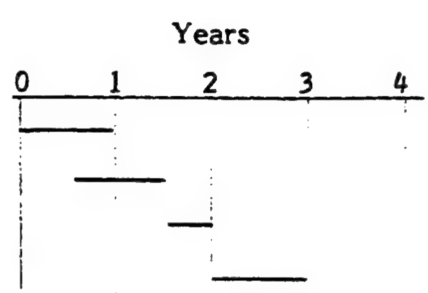
Phase IV: Damage Prediction and Analysis Manual

The data from all of the preceding phases would be combined and utilized to develop the final results. In addition to a technical summary of the analytical and experimental findings, the key product would be an extended damage prediction and analysis manual usable by environmental planners, airspace managers, and claims adjusters for assessing potential building damage from supersonic operations.

4.3.4 Schedule and Deliverables

The overall program is expected to require 3 years and be carried out according to the following schedule.

Phase I: Data Review
Phase II: Model Development
Phase III: Field Test
Phase IV: Damage Prediction/Analysis Manual



The deliverables for this program would consist of the following items:

Phase I:

- o Interim Report Summarizing the Existing Data on Sonic Boom and Blast Damage

Phase II:

- o Interim Report Outlining Preliminary Damage Prediction Model
- o Preliminary Test Plan

Phase III:

- o Final Test Plan
- o Report of Test Results

Phase IV:

- o Technical Report Summarizing All Pertinent Technical Findings
- o Damage Prediction/Analysis Manual

4.3.5 Estimated Resources and Supporting Facilities

	Costs ($1,000)			
	Phase			
	I	II	III	IV
Principal Investigator	30	20	20	30
Research Engineer	20	40	50	60
Technician		2	25	5
Logistics Support			25	
Expendable Supplies			25	
Test Structures			150	
Travel	—	2	15	2
	55	69	370	112
TOTAL		$606,000		

Supporting Facilities

Supporting facilities for this program would consist primarily of the dedicated supersonic flights. It is estimated that a total of 6 sorties, each consisting of 2 overflights on each of 6 days, would be the minimum requirement. Due to the greater control required for flight altitudes, some additional supporting Air Force ground control support may be required (communications and tracking).

However, it should be possible to combine this program with portions of the sonic boom modeling programs described in Volume II and thus provide considerable overall cost savings.

4.4 Program No. 4: Seismic/Acoustic Interaction

4.4.1 Objective

Establish an experimental data base for a practical prediction model for air-coupled seismic waves. These data are needed to validate or disprove frequent reports of seismically-related damage to structures that could be caused by this anomalous seismic/acoustic interaction.

4.4.2 Scope

This program should be limited to an experimental effort to acquire validating data for clarifying practical details of a prediction models based on a currently available analytical foundation. Anticipating the difficulty of conducting any type of experimental validation program involving dedicated flights, the test program would be carried out over a period of 2 to 4 months in an existing supersonic operating area and employing unmanned acoustic and seismic response measurement systems. This program may be combined with Program No. 3, Phase II under the Sonic Boom Monitoring effort outlined in Volume II.

4.4.3 Technical Requirements

Three phases are envisioned for execution of this program: I) Literature Review and Test Planning, II) Field Test, and III) Analysis and Model Development.

Phase I: Literature Review and Test Plan

The basic theoretical models outlined by Baron, et al. (1966), and Espinosa, et al. (1968) and the related work of Bass and Bolen (1984) would be reviewed to summarize the theoretical foundation for seismic coupling into the ground of the acoustic energy from a sonic boom. The objective of this review would be to support the optimum placement of an array of sensitive low frequency accelerometers for acquisition of the seismic data. In addition to basic measurement of the seismic response amplitude, the array should be designed to allow measurement of the velocity (speed and direction) of the "resonant" seismic surface waves excited under the coincidence effect of acoustic-seismic coupling when the seismic and acoustic trace velocities are equal.

In addition, a test site within a very active supersonic operating area should be selected, for which the "coincidence effect" can reasonably be expected to occur frequently. Available background information on local geology or seismic properties of the test sites should be acquired as well as data on typical supersonic operations to assist in the test plan development.

The test plan submitted to the Air Force for review and approval should clearly define:

- o Test site locations
- o Configuration of the acoustic and seismic measurement array
- o Recording instrumentation
- o Data acquisition and analysis procedures
- o Field test logistics and Air Force support requirements

<u>Phase II:</u> <u>Field Test</u>

The test should be carried out until a statistically reliable trend is established relative to seismic/acoustic interaction. It is expected that at least 2 months would be required to achieve this objective. However, a test period longer than 4 months is not recommended.

Instrumentation would consist of a modified version of the unmanned sound exposure meters recently employed for sonic boom monitoring in the Reserve MOA. For the seismic measurement systems, the modifications would consist of a change in the threshold detection logic for each event. This change would provide a reliable method for detecting the characteristically longer duration (1-3 seconds) of relatively narrow frequency spectrum seismic wave patterns that appear to result from resonant seismic/acoustic interaction. A limited number of full signature capture recordings of both the the acoustic and seismic signals would also be made near the beginning of the program.

<u>Phase III:</u> <u>Analysis and Model Development</u>

Results of the first two phases would be combined in this last phase to permit development of a practical and validated prediction model for seismic/ acoustic response.

Based on the existing knowledge of this phenomenon, it is anticipated that the model will show the potential for a substantially increased magnitude for the structural response to seismic vibration in a relatively narrow, low frequency spectrum. Based on the overall test results, the model should also provide a reasonable basis for making statistical predictions of the relative frequency for which this anomalous behavior will occur.

4.4.4 Schedule and Deliverables

The entire program is expected to require 1 year to complete, according to the following schedule:

		Years 2 — 3
Phase I:	Review and Test Planning	——
Phase II:	Field Test	——
Phase III:	Model Development	——

Deliverables would consist of the following reports.

Phase I: Interim report summarizing the analysis of the literature and defining the plan for field measurements.

Phase II: Test report on field measurements

Phase III: Final report defining the overall program results including the practical prediction model that could be incorporated into environmental planning guidelines.

4.4.5 Estimate Resources and Supporting Requirements

	Costs ($1,000) Phase I	II	III
Principal Investigator	10	15	15
Research Engineer	30	5	40
Instrumentation Engineer	5	60	
Technicians	2	50	10
Logistics Support		15	
Special Instrumentation		40	
Expendable Supplies		15	2
Travel	2	15	3
	49	215	70
TOTAL	$334,000		

No significant supporting requirements are envisioned beyond coordination of measurement activity with Air Force operations personnel. All other supporting activity would be provided by the contractor.

4.5 Program No. 5: Low Frequency Structural and Seismic Response

4.5.1 Objectives

Develop a broad, statistically valid data base and prediction model for non-damaging structural vibration and rattle noise inside conventional structures and seismic vibration of ground exposed to low frequency noise from Air Force flight operations and static test facilities.

4.5.2 Scope

The program would be designed to include activity in two general areas: 1) rattle noise and vibration due to low frequency excitation of buildings, and 2) seismic vibration due to low frequency acoustic excitation. In both cases, the low frequency noise of primary concern would be that generated by static engine testing. However, the program should also include consideration of low frequency energy from low altitude aircraft flight along military training routes. Seismic coupling of low frequency energy associated with secondary sonic booms (or rumble) well to the side of supersonic flight tracks may also be included if warranted. However, it is expected to have a very low priority at this point.

4.5.3 Technical Requirements

The following three-phase program should be carried out.

Phase I: Rattle Noise/Vibration Data Base

In Phase I, following preparation and acceptance of a test plan, conduct a field test program to obtain long term data, in a sample of 2 or 3 conventional buildings, on structural vibration and rattle noise levels during an extended period of operation (4 to 6 weeks) of a nearby static test facility. The data collection should include measurements during periods of normal activity by residents when the static testing facility is shut down. Include both building vibrations and external seismic vibration acoustic input in the data collection process. To augment this first part, which is oriented to locations near static testing facilities, collect similar building vibration and rattle noise data for a sample of 2 or 3

residences located on or very near the centerline of low level training routes for bomber aircraft. Also obtain data from these or similar buildings for structural response to other non-aircraft environments or everyday events such as door slamming. Both of these experimental phases would be coordinated with related efforts as described in Volumes II and IV.

Phase II: Rattle Noise/Vibration Prediction

Instrumentation anticipated for this phase would include both unmanned noise/vibration integrating (exposure) meters and full signature capture instrumentation and associated wide band tape recordings which can also be used, if appropriate, for some of the subjective testing activity outlined in Volume IV.

In Phase II, combine the data collected from this test program with related data from early sonic boom overflight programs in order to develop a suitable analytical model for predicting structural vibration and rattle noise levels due to low frequency excitation. The prediction model must accommodate the large statistical scatter that will be inherent in system parameters.

Phase III: Acoustic-Seismic Vibration

Finally, in a third phase, conducted partly in conjunction with Phase I, obtain measurements of seismic vibration levels near a static test facility and under a military training route. Combine these data with already available analytical models on seismic response of ground to acoustic excitation to provide practical prediction models and related land use guidelines.

4.5.4 Schedule and Deliverables

The total program is expected to require 2 years to complete and would follow the schedule outlined below. An early start on this program is important since its output is important to the psychophysical studies recommended in Volume IV.

		Years 0–1	Years 1–2
Phase I	Review and Test Planning	————	
Phase II:	Field Test		——
Phase III:	Model Development		—————

The deliverables for this program would be as follows.

Phase I:

- Test Plan (letter report) outlining the field test plan for acquisition of rattle noise and vibration data.
- Interim Test Report, summarizing the results of the field tests on rattle noise and vibration.

Phase II:

- Final Report, Rattle Noise and Vibration. This would summarize the overall results of Phase I and present a practical prediction model for rattle noise and vibration applicable to any land use planning or guidelines that require consideration of this type of environmental impact.

Phase III:

- Test Plan (letter report), outlining the field test plan for acquisition of low frequency seismic vibration data.
- Final Report, Seismic Vibration. This would summarize the results of the field measurements and present an overall prediction model suitable for application to environmental analyses when this stimulus is considered to be a significant factor.

4.5.5 Estimated Resources and Supporting Facilities

	Costs ($1,000) Phase I	II	III
Principal Investigator	15	30	15
Research/Instrumentation	10	40	20
Technician	25	5	30
Logistics Support	12		12
Expendable Supplies	13		3
Travel	10	5	10
	85	80	90
TOTAL	$255,000		

No major supporting activity from the Air Force is needed. However, support in the scheduling of field testing activity at Air Force facilities will be necessary. All other supporting activity and facilities will be contractor supplied.

APPENDIX A

Technology Review

Effects of Sonic Boom and Low Frequency Noise on Structures and Terrain

A.1 INTRODUCTION

This review of the technology in the subject area will cover (1) damage effects of sonic boom to conventional and (2) unconventional structures, (3) seismic responses to sonic boom, and (4) nondamaging response of structure and terrain to low frequency noise. Only the more significant of the approximately 165 references listed in Appendix B are cited in this limited review.

A.2 SONIC BOOM DAMAGE TO CONVENTIONAL STRUCTURES

A.2.1 Summary

Many technical papers and reports have been published during the past 25 years on structural damage caused by sonic booms. However, nearly all of the work, done more than 15 years ago, has been limited to studies involving relatively minor damage. The nature and extent of damage to conventional buildings from sonic booms for nominal overpressures up to about 30 psf, and the status of prediction models for such damage, can be summarized as follows:

1. Most of the damage will be minor, i.e., plaster cracks, broken windows, broken bric-a-brac, and masonry and tile cracks. The actual damage can only be predicted within, perhaps, several orders of magnitude (e.g., 10^{-5} to 10^{-2} broken windows per window-boom exposure for 6 psf nominal booms). This damage rate will increase by about 2 to 3 orders of magnitude for each doubling of sonic boom pressures up to approximately 30 psf.

2. The probability of more significant failures appears to be very small based on overflight results and theoretical analyses relating sonic boom loadings to other natural or man-made loadings. However, overflight test data and theoretical analyses of these other types of damage have been limited.

   These failures could be "triggered" by sonic booms if the structures were already deteriorated or damaged by other causes so that incipient failures were imminent.

Cumulative minor damage effects from prolonged exposure to low amplitude (approximately 2 psf) repeated booms was not evident from results of the few extended sonic boom tests. Very limited data are available which suggest that cumulative damage effects may result from repeated exposure to more intense sonic booms – greater than 10 to 15 psf (Blume, 1965b).

3. Considerable knowledge exists on natural forces and mechanisms that cause structural damage (e.g., "differential settlement" of soils, lumber shrinkage and swelling from humidity changes, etc.), and is useful for damage claim investigations and support of damage claims litigation. Comprehensive summaries are given in Wiggins (1969) and Blume (1965b) from experience in the U.S., and in Wilhelmsen and Larsson (1973) for experience in Sweden. This knowledge can provide strong support for preexistence of the damage or to show it was obviously caused by something other than sonic booms. If, however, preexistence of the damage or some obvious explanation is not evident, then support for nonpayment of a damage claim or for litigation may require an assessment of the likelihood or probability that a boom could cause the damage claimed.

Current technology for making such an assessment is similarly limited, as supported by the conclusions of Clarkson and Mayes (1972) in a comprehensive review of sonic boom building structure responses and damage (61 references cited):

> "The extensive series of overflight tests have provided valuable data on the order of magnitude of responses to be expected. These tests show that building structures in good repair should not be damaged at boom overpressures less than about 11 lb/ft^2. However, it is recognized that considerable loading variability occurs, owing to atmospheric effects, and that the residual strength of structures varies according to usage and natural causes. Thus, there is a small probability that some damage will be produced by the intensities expected to be produced by supersonic aircraft. The extreme statistical data required to predict this probability are not available and cannot be obtained in a laboratory or limited overflight

program. The alternative detailed study of each claim to ascertain categorically that a boom caused the damage will be time consuming and very expensive. Thus, at the moment, there is little firm scientific data on which to predict the damage likely to be caused by supersonic overflights."

Since Clarkson and Mayes' paper, relatively little significant work on the subject has been identified.

The status of the technology for predicting or assessing structural damage from sonic booms is also reflected in the findings and conclusions from three international conferences on sonic boom technology. These were the OECD Conference on Sonic Boom Research (1970); the ICAO Sonic Boom Panel (1970); and the Workshop on Sonic Boom Exposure Effects (1971). The primary focus of these conferences was on sonic boom effects from the SST. Their findings and conclusions were generally consistent with those indicated in the preceding discussions, as indicated by the following excerpts:

OECD Conference (1970) – Main Conclusions of the Conference:

> "... The major uncertainty with respect to boom effects on structures relates to the risk of <u>cumulative</u> damage over long periods of time."

Stockholm Conference (1971) – Concluding Statement by G. Weber in the structures portion of the proceedings:

> "On the structural side, the greatest interest concerns the possible fatigue effect due to the multitude of booms."

It is important to note that these conferences addressed the SST, which would cause large populations to be exposed to large numbers of sonic booms over long periods of time. The cumulative damage problem is considered less important relative to current Air Force needs where the primary structural damage problem becomes one of relatively few exposures (usually less than 2 or 3 per day) to sonic booms of low or moderate intensities from supersonic flights within supersonic operating areas.

Other gaps in the technology indicated by the findings and conclusions from these conferences included lack of adequate models for predicting minor building damage (broken windows, cracked plaster, etc.); and lack of knowledge of mechanisms by which landslides and avalanches are triggered.

The latter conclusion of the OECD Conference is relevant to the selection of Program No. 1 in this Research Plan. An equally relevant conclusion from this conference was that:

> "It was a consensus of the Conference that our ability to predict the effects of sonic booms on structures is not likely to be substantially improved through short-run research beyond that already programmed. A considerable body of data on the response of various types of structures to sonic boom overpressures already exists."

Consider, now, key aspects of this existing body of data.

A.2.2 Data from Damage Claims in Overflight Tests Over Urban Areas

Tables A-1 and A-2 summarize the damage claims data from most of the supersonic overflight tests in the U.S. and Europe from which statistical damage claim data are available. A detailed analysis of formal claim records for FY 1966 contains additional data on this early history (Grubb, 1967).

Table A-3 summarizes the specific Air Force experience with available data on structural damage claims from sonic booms from 1956 to 1970. (Little data have been located for the period after 1970.) Ignoring any corrections for inflation during the time period covered by these data, the following general observations can be made:

- o For the claims data in Table A-1 for flights over urban areas, the value of the claims paid ranged from $19 to $430 per claim with an average of $133 per claim. The comparable Air Force figures from Table A-3 range from $88 to $176 with an average of $114 per claim.
- o The number of claims settled per million boom-person exposures ranged from 0.62 to 10.2 with an average of about 4.0 claims settled per million boom-person exposures.
- o As indicated in Table A-2, a major part of the damage relates to broken windows (an average of 75 percent claims paid for all the studies considered in this table).

Table A-1

Sonic Boom Damage Data
(Derived from Wiggins (1969), and Clarkson and Mayes (1972))

No.	Place	Date	No. of Overflights	ΔP Median, psf	*Boom-Person Exposures, (BPE) x 10^6	No. of Complaints	No. of Damage Claims	% for Plaster Damage	No. of Damage Claims Settled	% of Total Claims Settled	Total Pmts per 10^6 BPE	Total Pmts $	$/Claim	No. of Claims Settled/ 10^6 BPE
1	St. Louis	1961-62	150	1.8	390	5,000	1,624	43%	828	51%	$151	58,648	$ 71	2.12
2	Oklahoma	1964	1,253	1.2	462	15,452	4,901	---	286	6%	$266	123,061	$430	0.62
3	Chicago	1965	49	1.8	304.5	7,116	2,964	---	1,452	49%	$377	114,763	$ 79	4.77
4	U.S. Military Total **	1956-70	---	---***	---	---	41,617	---	15,398	37%	---	1,716,639	$112	---
5	Edwards AFB	1966	163	<3	7.34		51	19.6%	15	29.5%	$185	1,358	$ 90	2.04
6	Operation "Summer Sky," U.K.	1967	11	1	50		788	11.8% for $3400 of $9800 total pmts	512	65%	$195	9,750	$ 19	10.2
7	Nausta, Vidsel Jokkmokk, villages, Sweden	1969	53	1.4 to 15	---		370	7.5%	52	14%	---			
	*Total #1-3, 5, 6, only		1,626		1,214		10,328		3,093*	30%	$253	$307,580		

*Population exposed times the number of supersonic overflights.

**Includes the data listed above.

***Varies up to about 100 lb/ft^2

Table A-2

Breakdown of Claims Data for Structural Damage Incurred During Exposure to Sonic Boom in the United States (from Wiggins, 1969)

Overflight Locations	Average Δ p (psf)	Glass			Wallboard & Plaster			Bric-a-Brac			Structural & Other			Total No. Claims	No. Paid Claims	% Paid	Claim Compl (%)	Paid Damage Incidents/ Million People
		Claims (% Total)	Paid (% Glass)	Paid (% Total)	Claims (% Total)	Paid (% Plas.)	Paid (% Total)	Claims (% Total)	Paid (% B-a-b)	Paid (% Total)	Claims (% Total)	Paid (% S&O)	Paid (% Total)					
Engineer Investigators:																		
Oklahoma City*	1.2	12	18	37	56	5	48	2	34	12	30	1	3	4901	287	5.9	50	0.4
St. Louis '61	1.8	30	40	36	49	22	33	6	100	18	19	19	13	157	52	33	–	1.2
Average	–	21	26	37	53	14	40	4	67	15	25	10	8	–	–	20	50	0.8
Air Force Investigators:																		
Chicago	1.8	–	–	75	–	–	14	–	–	6	–	–	5	3156	1455	47	44	4.3(6.1) †
Milwaukee	1.8	28	68	47	42	31	32	7	79	13	23	14	8	639	246	42	67	2.0(2.8) †
Pittsburgh	1.8	43	74	71	25	21	12	6	38	10	26	12	7	1125	502	46	60	2.8(6.8) †
St. Louis '61	1.8	35	–	–	34	–	–	12	–	–	19	–	–	1624	825	51	33	2.6 –
St. Louis '65	1.8	27	73	44	46	42	42	5	69	7	22	13	7	491	221	45	35	2.7(5.8) †
Average	–	29	71	59	42	31	25	6	62	9	23	13	7	–	–	46	48	2.9(5.5) †
Sonic Boom Accidents:																		
Cedar City	17	80	100	80	13	100	13	1	100	1	6	100	6	97	97	100	–	43,700
Wash. Ct. Hse.	22	78	100	78	–	–	–	–	–	–	–	–	–	198	160	97	–	16,000
Panama City	15	66	93	77	16	30	6	9	91	10	20	28	7	122	97	71	–	303
Boston	5	56	90	61	6	100	6	22	75	20	16	67	13	18	15	84	–	28
Average	–	68	96	75	10	77	8	10	89	8	12	65	9	–	–	88	–	–

*Remert Adjustment Company investigated most claims.

**Clark, Buhr & Nexon investigated all claims immediately after complaints for 17 of 76 booms.

† SRI reports these values.

Table A-3

Air Force Structural Damage Claims Data/1

	Claims Made		Claims Paid		
		Total		Total	
FY	No.	$1,000	No.	$1,000	$/Claim
1956	36	12.2	21	1.9	91
1957	372	157.1	286	18.9	66
1958	522	196.2	235	39.5	168
1959	632	285.2	243	21.4	88
1960	681	107.8	227	20.3	89
1961	1,146	703.2	527	57.3	109
1962	3,092	990.5	1,451	132.4	91
1963	7,200	4,022.7	2,268	239.5	106
1964	5,102	3,544.8	1,654	182.5	110
1965	9,574	4,938.0	2,490	256.0	103
1966	4,856	3,284.0	2,123	211.1	99
1967	2,216	1,732.1	1,080	145.3	135
1968	3,402	2,564.7	1,391	191.5	138
1969	1,656	6,030.8	814	115.1	141
1970	1,130	2,004.6	479	84.1	176
			Mean		$114
			Std. Dev.		$31

/1Source: HQ USAF/LEEV

- o All of the overflights cited were conducted between 1961 and 1970. Thus, the claims experience applies to structures and types of construction that existed between 15 and 24 years ago, as well as to aircraft types and flight conditions during that time. Also, the claims experience reflects the public attitude towards filing damage claims during that period, which is generally different today, leaning towards more liberal settlements for claimants in court proceedings.

- o With the exception of some of the 53 overflights in Sweden (Table A-1), some of the U.S. military overflights (Table A-1, and the four accidents listed in Table A-2, all of the nominal overpressures were less than 3 psf. This is significant in view of the sensitivity of damage probability to the magnitude of the overpressure which will be shown later for windows.

Even with these limitations on the use of damage claims data for prediction of structural damage, the overall trends in the claims data provide at least some guidance for the Air Force in planning the anticipated continuing burden of these small claims from residents near active supersonic operating areas. While the data in Tables A-1 and A-2 are primarily for the extended SST simulation overflight tests in urban areas, the average damage claim rates seem to be roughly consistent (within an order of magnitude) with current Air Force experience based on a detailed examination by Wyle of 3 years of sonic boom damage claims submitted to Nellis AFB.

The data presented so far are considered inadequate to provide a basis for a damage assessment model at higher sonic boom pressures. Wiggins (1969) has attempted to develop such a model for windows by combining the claims damage data with window damage data available from other sources, including results from one NASA low altitude sonic boom test in Nevada of specially constructed window specimens (Maglieri, et al., 1966) and an FAA test in the White Sands Missile Range (Blume, 1965a,b). With these results, plus data from an accidental explosion, and the overflight data from Tables A-1 and A-2, Wiggins developed the statistical prediction model for glass damage illustrated in Figure A-1. (Note that the abscissa is the probability of window failure per boom exposure.) Before considering the results portrayed in this figure any further, however, it is desirable to examine these special overflight tests more carefully.

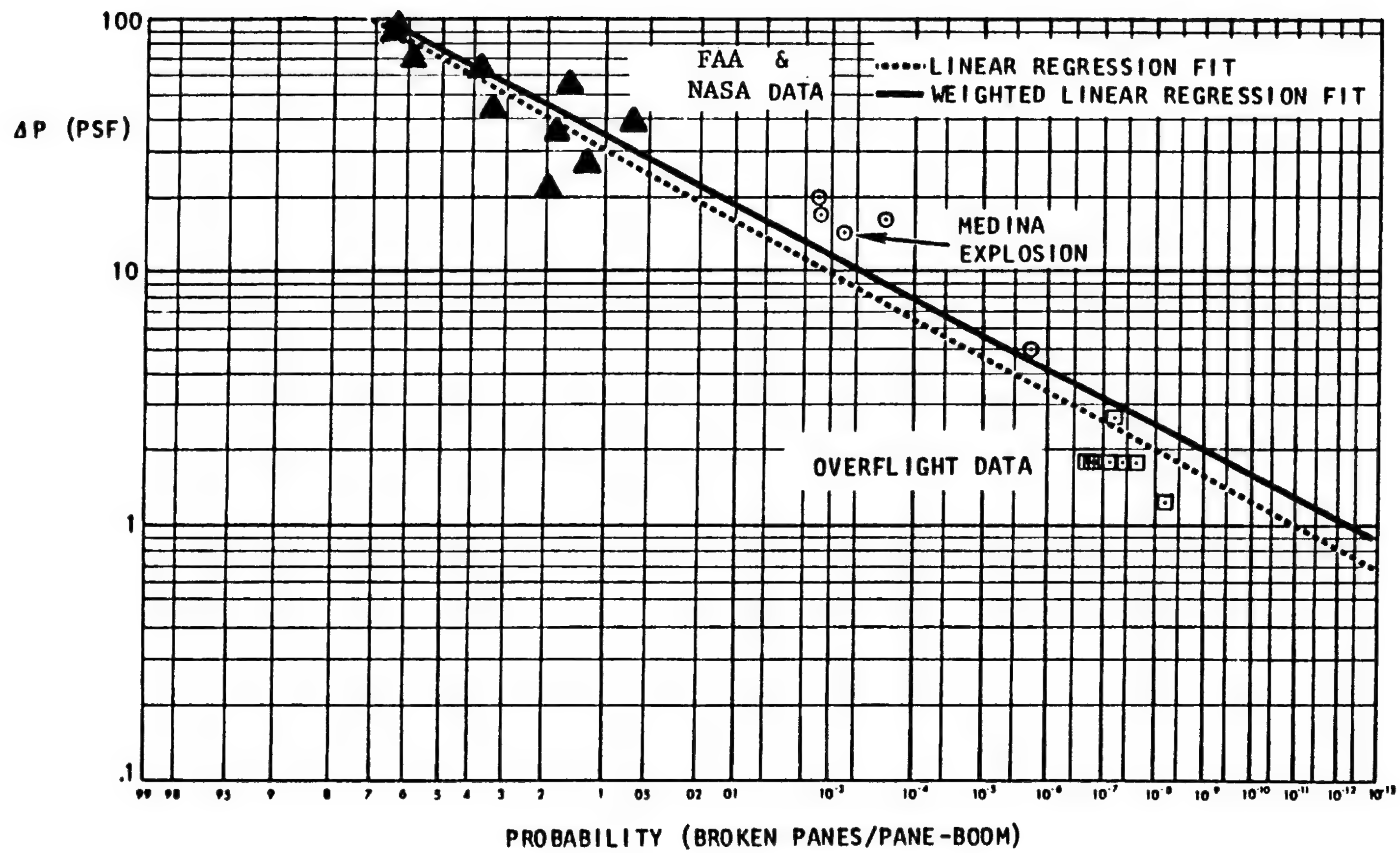


Figure A-1. Accident and Paid Overflight Glass Claims Plotted Together with Regression Curves Computed from NASA Test Information (based on Wiggins, 1969)

A.2.3 Special Overflight Test Programs Involving Response or Damage Data

Consider, first, the programs which involved overflight tests where direct monitoring of damage was accomplished.

Only two such test programs had been conducted by 1969 which supplied damage data useful for damage predictions. These were the NASA tests near Indian Springs, Nevada (Maglieri, et al., 1966) and the White Sands Missile Range tests (Blume, 1965b). Only glass damage was recorded at Indian Springs. Glass, plaster and bric-a-brac damage was categorized during the White Sands test program. Two other test programs (Oklahoma City, Andrews, 1965b) and Edwards Air Force Base (SRI, 1967) have been conducted which involved direct measurement of structural response, but no damage resulted in the test structures.

The glass damage curves determined from the Indian Springs and White Sands tests are shown in Figure A-1 by the black triangles at high overpressures. However, there are some questions to be raised about using these data for damage estimates at high overpressures.

1. In the Indian Springs tests, the window test specimens were carefully constructed and located on one side of small closed boxes which served as test jigs (Maglieri, et al., 1966). This mounting does not correspond to a real window configuration in a building.
2. The only substantial window damage from the White Sands tests, involving some specially built test buildings and existing buildings, occurred during one unscheduled flight where the overpressure reached 38 psf (Blume, 1965b).
3. In neither test was there any observation of glass fragments being propelled beyond the window frame as was observed in a subsequent Air Force test (Nixon, et al., 1968).

This later test involved a unique window damage pattern that has not been reported anywhere else. While the structural damage test results are largely qualitative, they deserve more careful examination.

The Air Force program (Nixon, et al., 1968) is the only controlled sonic boom test program conducted in the U.S. which exposed any normal structure to above 30 psf overpressure. The structures consisted of "very old frame and brick

buildings in poor states of repair and both old and new campers and trailers." No building response measurements were obtained at the two buiding sites (the towns of Belmont and Stone Cabin, Nevada). The principle findings were:

- At the nearly abandoned town of Belmont, the maximum overpressures measured were 24 and 33 psf for the two overflights which passed about 2,600 ft from the town center (2,000 ft from the nearest building).

- At Stone Cabin ranch, the maximum overpressure was 50 psf (at 6 ft above the ground at 1 mile from the track) for the one overflight at an altitude of 210 ft.

- Damage was confined to glass breakage, plaster cracking, and furnishings (bric-a-brac) falling from shelves.

- Usually glass breakage (at these buildings) occurred for the window facing the oncoming aircraft and, in some instances, glass fragments were propelled up to 12 ft.

- A small side window of a camper parked 100 ft from the track (where overpressures would have been of the order of 50 to 100 psf) was also broken and glass (fragments) flew as far as 12 ft in the direction of the aircraft approach.

In summary, the high overpressure data employed by Wiggins in his window breakage prediction model portrayed in Figure A-1 may be suspect since the test configurations and failure patterns may not be representative of more typical field conditions.

A.2.4 Alternate Damage Prediction Models

Consider, now, alternate approaches for damage prediction at high overpressures. One is an empirical statistical approach carried out by Hershey and Higgins (1976) which combines measured response data and statistical models on data on response or damage behavior of various structural components. The other approach recommended for this Research Plan includes application and extrapolation of both measured sonic boom and blast loading response and/or damage data.

A.2.4.1 Statistical Damage Prediction Methods

The statistical prediction approach used by Hershey and Higgins (1976) is illustrated, conceptually, in Figure A-2. Statistical distributions of the loading and some measure of fragility, such as window breaking pressure, are determined. The area under the region where the curves overlap represents the damage probability. The result of applying this process to window damage as well as to other types of components subject to sonic boom damage is shown in Figure A-3.

The method is sound but, of course, the results are only as good as the data used. As Clarkson and Mayes (1972) have pointed out:

> "Although the general shape of the probability distribution curves (of loading and material strength) is known, the critical extremes of very low probability are not clearly defined. The effect of different assumptions becomes most marked in this region. For example, Seaman (1967) produced estimates of probability for window damage ranging from $2x10^{-4}$ to $2x10^{-9}$, depending on the assumed probability distribution."

The increasing scatter at the lower damage probabilities in the predictions shown in Figure A-3 could very well illustrate the problems cited by Clarkson and Mayes. The technology addressed by the analysis of Hershey and Higgins was oriented toward the supersonic transport and overpressures around 2 psf. For damage from low altitude supersonic operations involving higher overpressures, the absolute probability of damage will, of course, be much higher, but the relative uncertainty in the probability of damage will still be high due to the inherent variance in both the sonic boom loading and the structural fragility at all sonic boom damage levels.

The probability distributions and sources of data that went into Hershey and Higgins' loading distribution for glass are summarized in the sketch on Page A-15. Although they formulated the loading in terms of an extreme fiber stress in the center of a simply-supported rectangular plate model, their calculations actually compared peak pressures on the windows with uniform breaking pressures supplied by Libbey-Owens-Ford Company. The stress model they recommend and the failure data they used is inconsistent with conclusions on glass breakage observations by others (Wiggins (1965, 1969; Wilhelmsen and Larsson, 1973) to the effect that uniformly loaded windows will fail by cracking somewhere close to the center of the pane, but the most common glass failure from sonic booms involves simple cracks at corners of the glass section. This type of failure results from either improper mounting of the glass or distortion of the mounting as a result of structural movement.

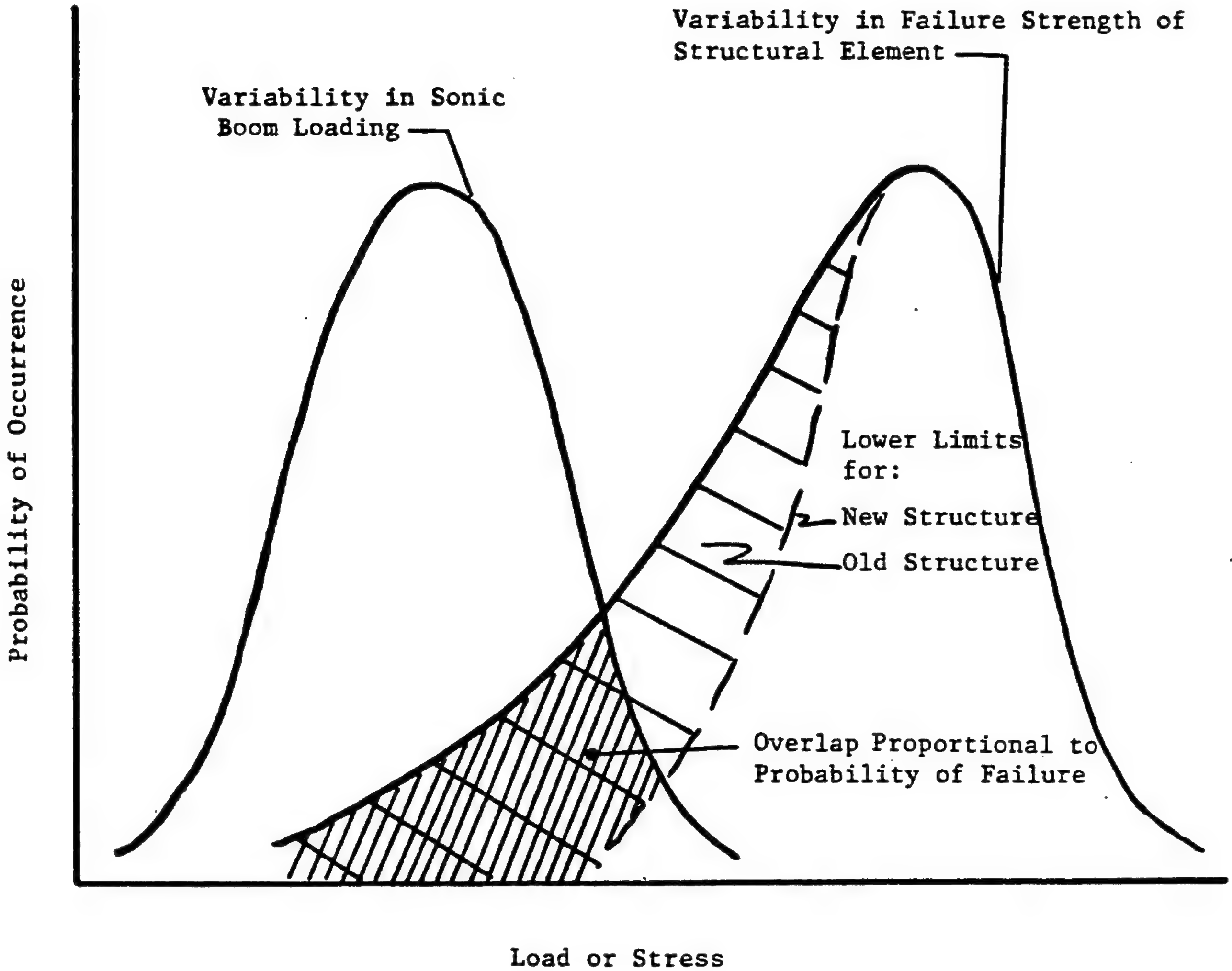


Figure A-2. Conceptual Illustration of Statistical Approach to Damage Prediction Which Accounts for the Statistical Scatter in (Sonic Boom) Loads and Structural Strength of a Given Type of Component, Such as a Window.

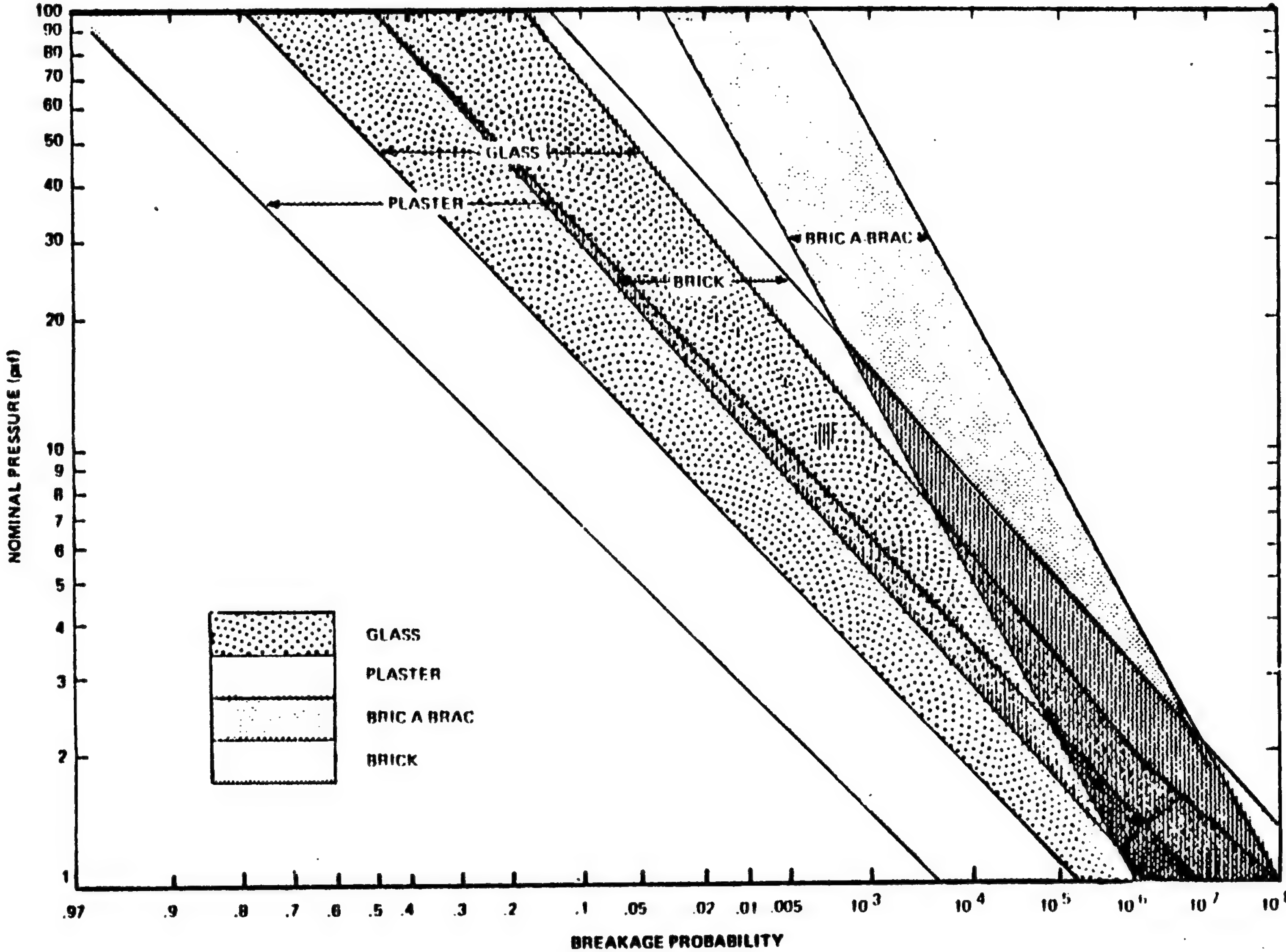


Figure A-3. Ranges of Breakage Probabilities for Glass, Plaster, Bric-a-Brac, and Free-Standing Brick Walls of High Bond Mortar (from Hershey-Higgins, 1976)

MAXIMUM STRESS FOR NOMINAL OVERPRESSURE P_o:

$$\sigma_m = P_o \left(\frac{P_f}{P_o}\right) \left(\frac{P_e}{P_f}\right) \left(\frac{\sigma_d}{P_e}\right) \left(\frac{\sigma_m}{\sigma_d}\right)$$

DAF
500 Values available from Edwards AFB and White Sands Tests

(Static Stress produced by P_e)/P_e
Deterministic Stress factor from structural model — flat plate

(External overpressure on structure)/Free-Field
900 values from White Sands Tests

Free-field/Nominal
3500 values from Oklahoma City Tests

Nominal overpressure

P_o	=	Nominal overpressure (includes a conventional value of the ground reflection coefficient of 1.9)
P_f	=	Peak free field overpressure (includes a doubling effect from ground reflection)
P_e	=	Peak value of external overpressure on a structure
σ_d	=	Stress produced by a static pressure equal in magnitude to P_e.
σ_m	=	Maximum stress in the structure

Hershey-Higgins Damage Prediction Model for Glass

Another aspect of Hershey and Higgins' work, which raises further questions as to the validity of some of their assumptions and conclusions, is their omission of any comparison with or reference to Wiggins' extensive predictions published in 1969 and their conclusion, not consistent with Wiggins' data, that their results "tend to agree well with sonic boom claims experience."

Since they also applied the method to other structural components/ materials, as shown in Figure A-3. These results may be as questionable as are their predictions for probability of glass breakage.

A.2.4.2 Extrapolation of Sonic Boom and Blast Data

The other alternative for predicting sonic boom damage at high overpressures which does not depend on the very limited but possibly suspect high overpressure sonic boom damage data is outlined in detail in Section 4.3 of these Research Plans. The concept is illustrated again, for convenience, in Figure A-4. Concrete evidence of the efficacy of this approach is provided by the data in Figure A-5(a) and (b) illustrating the basic linearity but different structural response to various impulsive loads. Two key elements of this approach for evaluating blast damage at higher pressures are: (1) the very different pressure time history pattern for high intensity (i.e., near field) sonic booms, and (2) the application of shock spectra (or dynamic amplification factor - DAF). An example of the first point is illustrated in Figure A-6 showing the major change in pressure time history of a sonic boom as aircraft elevation changes from 590 ft to 60 ft AGL (Maglieri, et al., 1966).

The second point is illustrated in Figure A-7 which shows envelopes of computed values of the shock spectra (or DAF) for dynamic deflection response to the sonic boom signatures for three different aircraft types as a function of the resonance frequency of the responding structural component. The point is that these dynamic response spectra (e.g., ratios of peak dynamic response to the corresponding response to a static load with a magnitude equal to the peak dynamic load) vary significantly, and predictably, with the time history of the pressure signature.

A necessary ingredient of this approach is the availability of blast response data on structures. The recent extensive studies by the U.S. Bureau of Mines (Siskind, 1976, 1980a,b; Stagg, 1984) plus numerous other blast response and blast

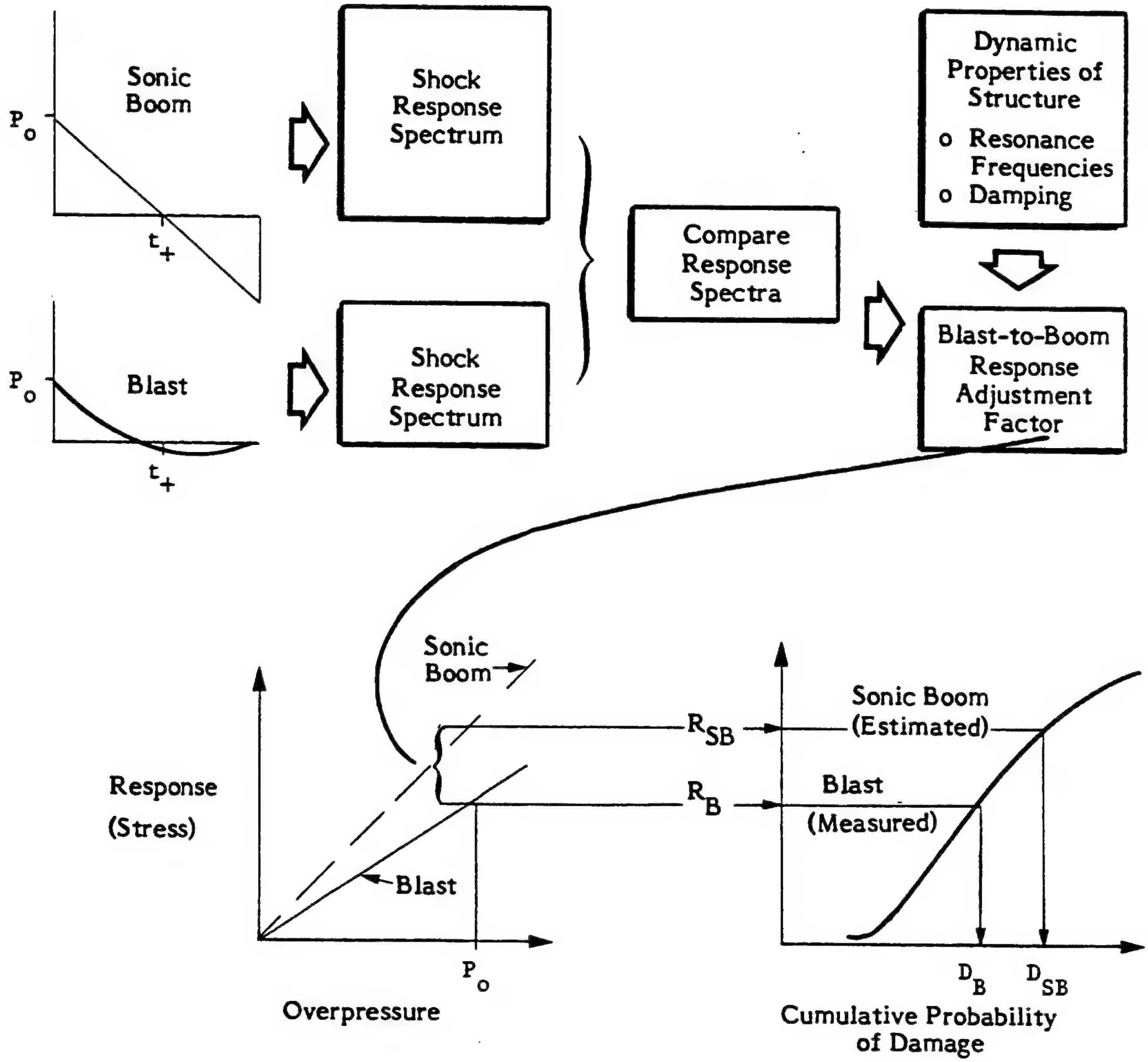
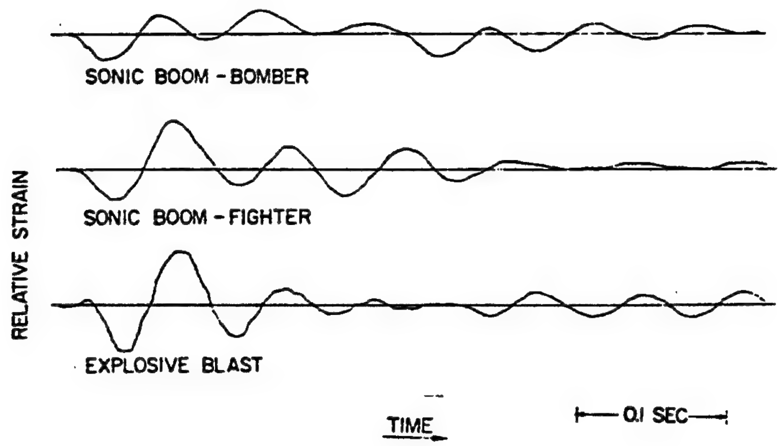
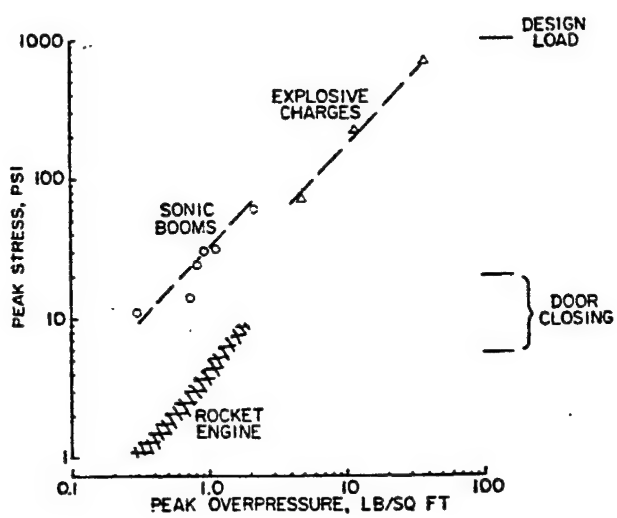


Figure A-4. Conceptual Illustration of How Measured Blast Response and Blast Damage Probability Data for a Given Structure Will be Used to Estimate Response and Damage Probability from Sonic Booms for the Same Structure Based on Comparison of Shock Response Spectra for the Two Different Types of Excitation. (The procedure is not restricted to the case illustrated where the peak overpressure P_o and positive phase duration t_+ are comparable.).



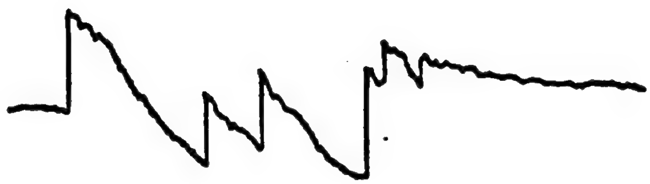
(a) Strain measurements of a vertical stud in a test building to transient loads from sonic booms or blasts.



(b) Peak vertical stud stresses as a function of peak overpressure for various types of excitation.

Figure A-5. Data Illustrating the Ability to Extrapolate Blast Response Data to Project Estimated Response to Sonic Boom (from Mayes & Edge, 1964).

(a) Altitude = 60 feet; M = 1.124.



(b) Altitude = 95 feet; M = 1.088.

(c) Altitude = 190 feet; M = 1.068.

(d) Altitude = 340 feet; M = 1.145.

(e) Altitude = 590 feet; M = 1.065.

Figure A-6. Pressure Time Histories Measured at the Ground for Airplane A at a Range of Altitudes from 60 to 590 ft (from Maglieri, et al., 1966).

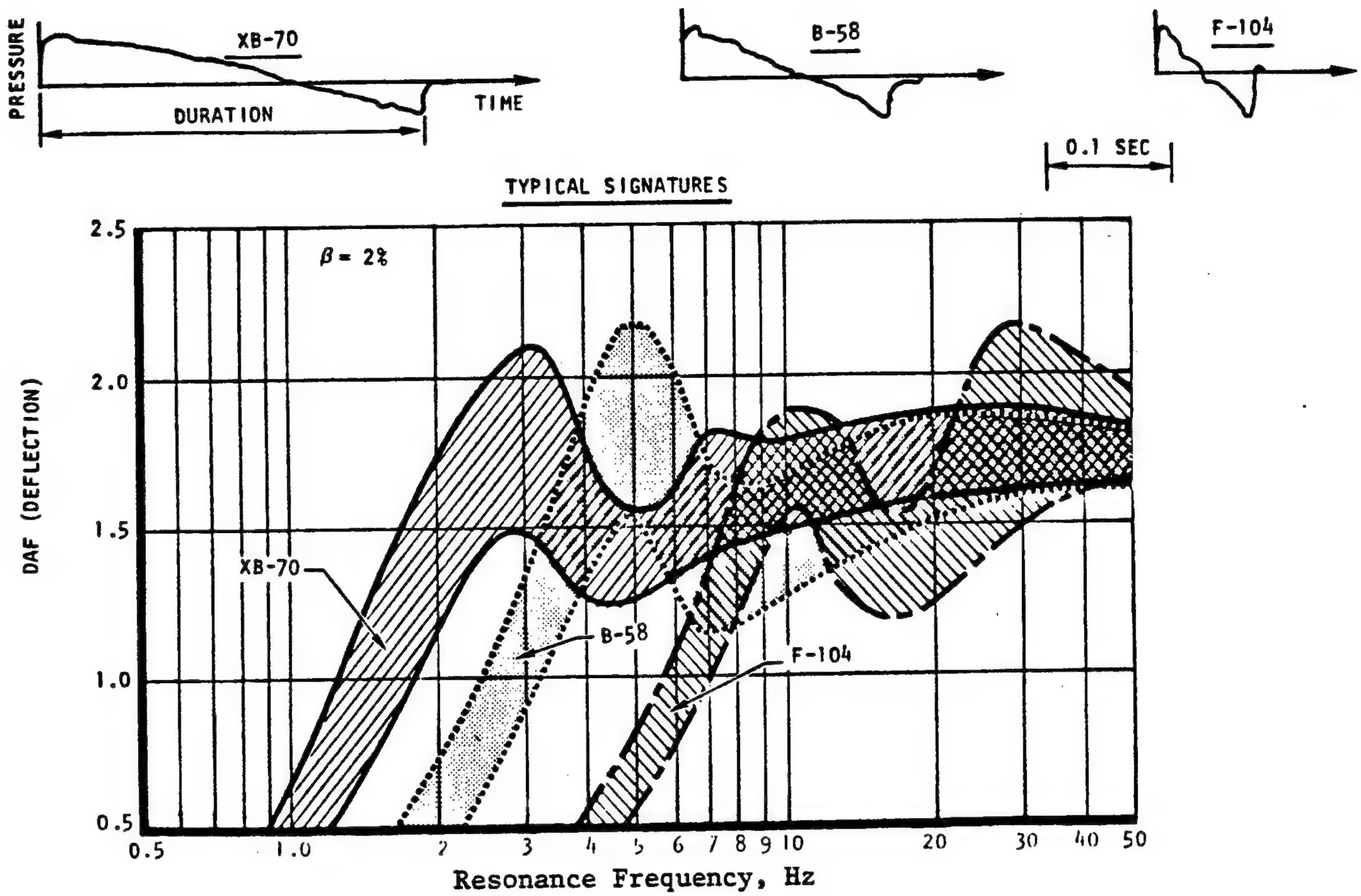


Figure A-7. Envelopes of Damped System DAF to Free-Field Loading (from Blume, 1967).

damage studies (Northwood, et al., 1963; National Bureau of Standards, 1971), particularly those summarized or identified in ANSI S2.20 (1983), ensure no lack of such data.

A.2.5 Theoretical and Related Experimental Studies of Response to Sonic Boom

Throughout the evolution of knowledge on response of structures to sonic boom loads, analytical studies and related experimental studies have been carried out. Examples of these studies include:

- Simple single-degree-of-freedom models appropriate for use with shock spectra (Wiggins, 1969; Sutherland, 1968) and classical modal analysis (Wahba, 1984).
- More detailed analyses of response of windows to sonic boom (McKinley, 1964; Seaman, 1967) and supporting experimental studies (Pallant, 1973).
- Finite element models of dynamic response of frame structures, applying technologies similar to that currently employed for analysis of aerospace systems (Shepherd, 1986).
- Analysis of the response of single or coupled room volumes excited by sonic boom pressure on an open window (Bressers, 1983; Wahba, 1977).
- Theoretical analysis of the diffraction of the free-field sonic boom pulse by two- or three-dimensional obstacles (Ting and Kung, 1970).

These latter two types of analytical studies have also been frequently supported by model (Peschke, et al., 1971; Slutsky and Arnold, 1972) or analog studies (Lin, 1970).

A.3 SONIC BOOM DAMAGE TO UNCONVENTIONAL STRUCTURES

As indicated in Section 3.0 of the main body of this volume, currently available information about the damage potential for sonic booms to various unconventional structures is either technically or not adequately disseminated, thus hindering effective resolution of public concerns about these special structures.

Representative information that is available on such structures as wells, water tanks, historical monuments or archaeological structures, or large radio astronomy antennae can be summarized as follows:

- Local geological surveys and well drillers' log records will assist in clarifying the physical structure and status of wells that may be exposed to sonic booms.

- For above ground water tanks, the extensive dynamic analyses (Haroun, 1983) and blast load studies (Norris, et al., 1959) will be very pertinent and beneficial. Evaluation of surface water tanks can still use some of the results from these studies.

- Directly relevant data on potential sonic boom effects on historical monuments or archaeological structures are available from one limited experimental study (Battis, 1983) of seismic response of Indian archaeological structures (e.g., Indian caves) in the Valentine MOA, Texas, and rock outcropping in a nearby area to supersonic flights of F-15 aircraft expected to generate overpressures of about 3 to 4 psf. The measured seismic responses were less than 8 percent of strict local codes for blast damage and were comparable to seismic motion experienced during local earthquakes. Note that, assuming linearity of response, a twelve-fold increase in overpressure to about 36 to 50 psf could have caused seismic responses approximately equal to the blast damage limits. However, since it is common in such codes to set lower allowable blast-induced seismic vibration limits for historical buildings or archaeological structures, this extrapolation may not provide a true picture of possible risk of seismic vibration damage from high amplitude sonic booms. Additional direct support to this technology is provided by the nonspecific analytical and experimental studies on seismic response to sonic booms discussed later.

Indirectly relevant data on potential damage to sensitive structures from sonic boom are clearly available from the vast knowledge base on structural effects of earthquakes. Data on normal microseismic activity (Frantti, 1963) as well as on earthquake damage problems (e.g., Lee and Shepherd, 1984) is clearly relevant.

Potentially detrimental sonic boom excitation of radio astronomy antennae located in the southwest near some of the supersonic operating areas can be addressed from the viewpoint of acoustic loads on frame structures (Sutherland, 1968) (unlikely to be significant) and seismic loads. For the latter, space frame vibration analysis methods (Shepherd, 1986) will be very beneficial if required.

A.4 TERRAIN EFFECTS OF SONIC BOOM

A.4.1 Normal Seismic Responses

The basic seismic response of ground to sonic boom loads has been the subject of intensive analytical and experimental studies (Goforth and McDonald, 1968; and Cook and Goforth, 1970, to name a few). Typical measured seismic response patterns are illustrated in Figure A-8. Note how the seismic response exhibits downward-going peaks, one at the beginning and at the end, of the "N-wave" excitation. The general trend from a large number of such tests is that the ratio of peak seismic velocities to peak overpressure is of the order of 0.5 to 2 in./second per 1 psi (144 psi).

Ground velocities of about 0.4 in./second were in fact observed for one low altitude (approximately 200 ft AGL) supersonic flight test (Maglieri, et al., 1966) where the peak overpressures were in the range of 40 to 120 psf. Seismic motions of this magnitude, induced only by flight at these very low altitudes would, in fact, be close to, but not necessarily exceed, damage threshold limits for blast-induced ground vibration of about 1 in./second (Siskind, 1980a,b). In general, this basic seismic response to sonic booms appears to be sufficiently well-defined so that new research is not required to provide practical damage prediction models. This is not true, however, for two other aspects of terrain effects:

- Seismic/acoustic interaction, and
- Avalanche or slide triggering potential.

A.4.2 Seismic/Acoustic Interaction

For the basic seismic response just discussed, the ground responds in a linear fashion to the pressure pulse as a medium with an acoustic admittance of about 1 in./second per psi. However, if the trace velocity of the sonic boom overpressure wave on the ground coincides approximately with the wave velocity of local Rayleigh (surface) waves of the ground, a sort of resonance effect is achieved and the seismic response appears to be quite different. This problem was addressed in detail, analytically (Baron, et al., 1966), and was not considered significant due to the low probability of the seismic-acoustic velocity coincidence occurring. However, subsequently, an experimental demonstration of the effect was achieved, as illustrated in Figure A-9 (Espinosa, et al., 1968). The upper part of the figure

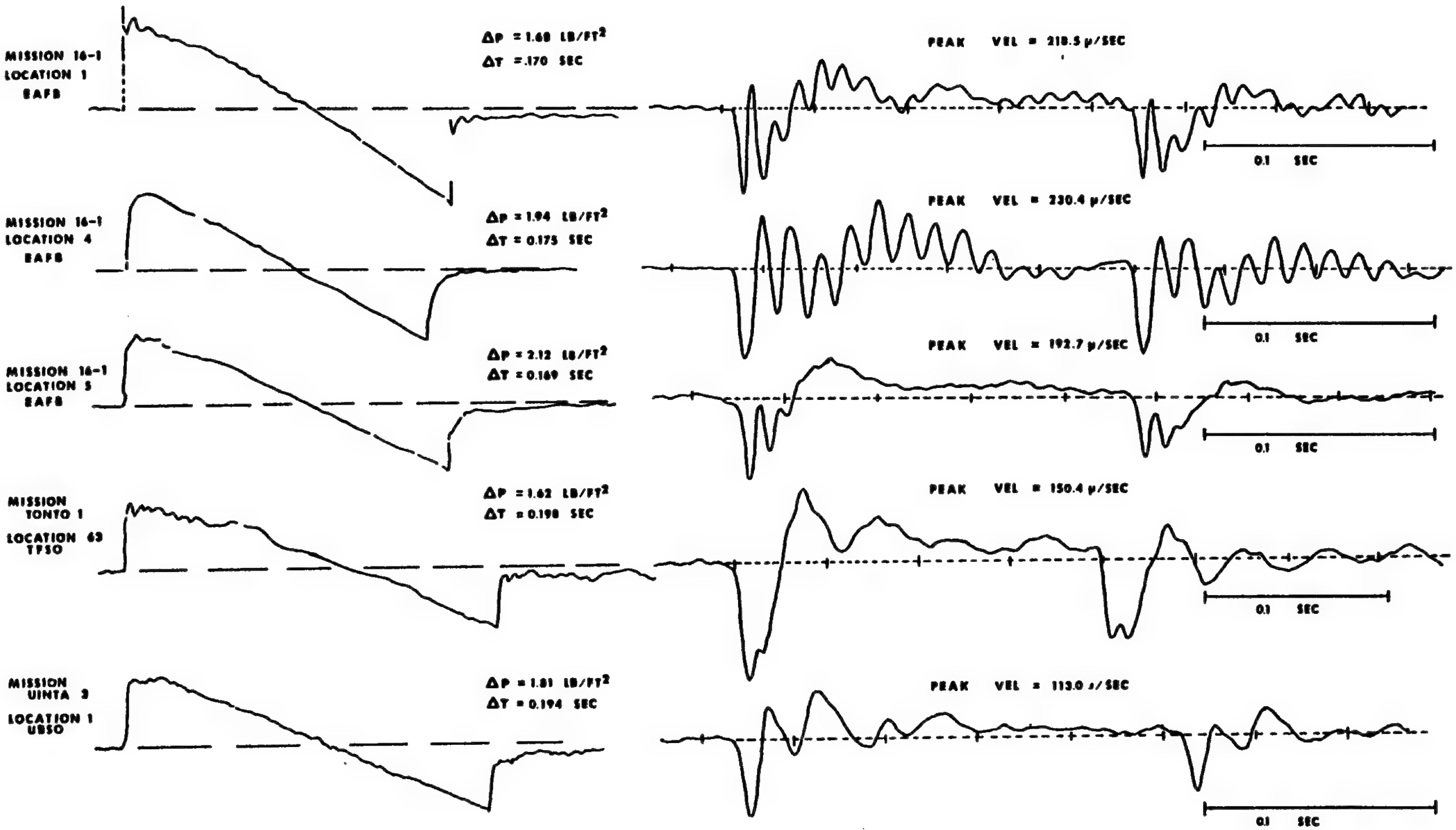
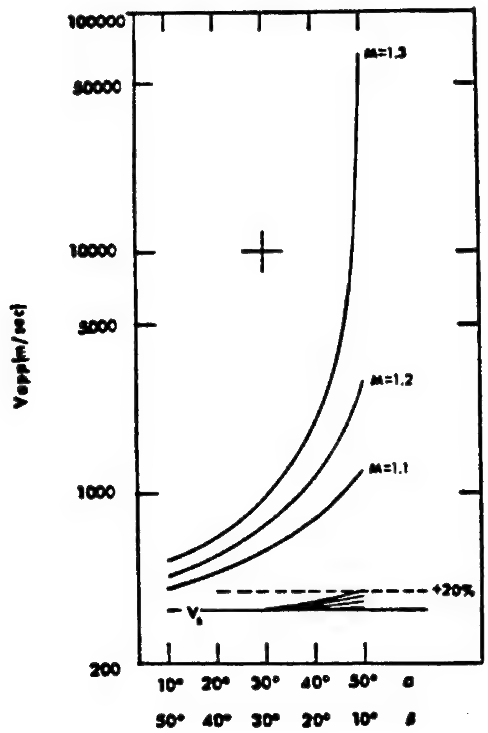
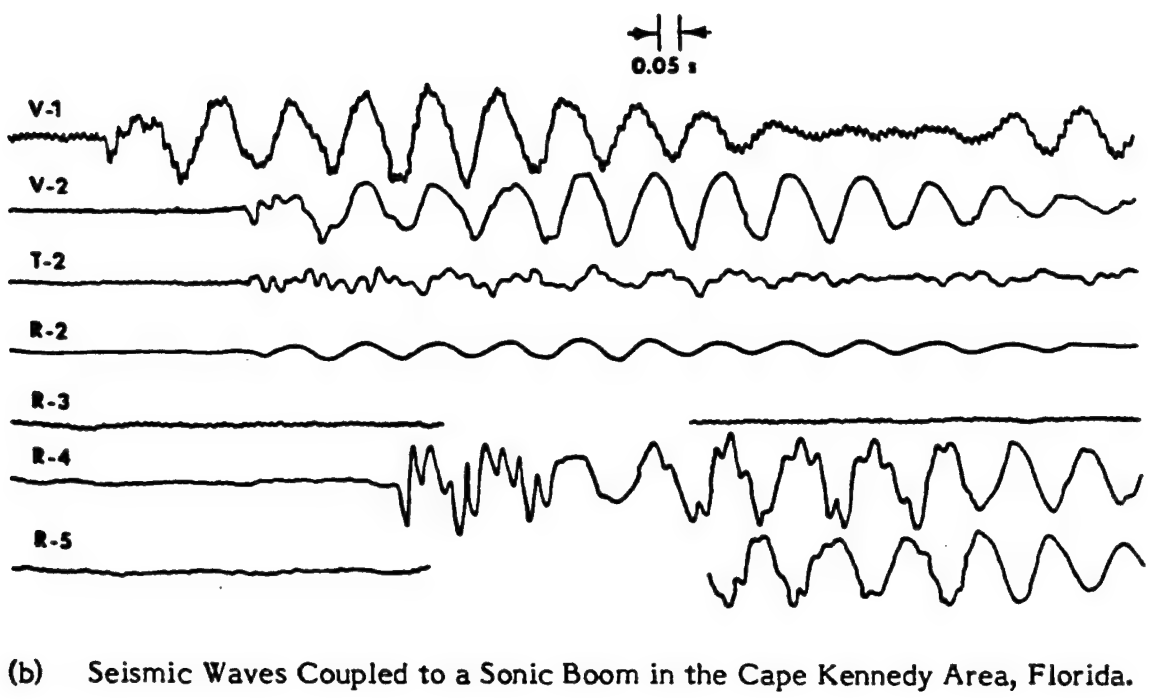


Figure A-8. Seismograms and Similar Pressure Signatures Recorded at Five Locations for B-58 Overflights Showing the Variations of the Seismograms with Geological Environment (from Goforth & McDonald, 1968).



(a) Apparent Wave Velocity as a Function of Diving and Climbing Angles. The parameter is diving and climbing airplane flights from 1.1 to 1.4 Mach numbers.



(b) Seismic Waves Coupled to a Sonic Boom in the Cape Kennedy Area, Florida.

Figure A-9. Evidence of Seismic-Acoustic Coupling from Sonic Boom Excitation of the Ground (from Espinosa, et al., 1968).

shows the theoretically predictable trace velocity, on the ground, of the sonic boom pattern for several Mach numbers and aircraft climb or dive angles. (Note that the lowest velocity is sonic.) The lower part shows evidence of a reinforced (or coincident) seismic wave that occurs when its wave velocity matches the sonic boom trace velocity. Instead of the more typical short transient seismic responses to a sonic boom illustrated earlier in Figure A-8, the ground responds with a sinusoidal type motion (in this case, at a frequency of about 6 Hz) for about 1.5 seconds — much longer than the duration of the sonic boom N-wave excitation. The result is that any structural system with a resonance frequency in this range would be driven, for several cycles, by this motion and hence would potentially respond to a much greater degree than it would to the shorter transient motions of Figure A-8. New research is considered necessary and feasible to more clearly define this phenomenon which may help explain anomalous claims of seismically-induced damge from sonic boom often presented by the public (U.S. Air Force, 1979a, b, c).

A.4.3 Avalanche or Slide Triggering by Sonic Booms

Anecdotal evidence exists to the effect that sonic booms have been used to intentionally trigger unstable snow avalanche-prone areas in Glacier National Park (The Seattle Times, 9 February 1960). It is also customary, in Switzerland, to cancel supersonic flights of military aircraft over avalanche-prone areas during recognized moderate to severe avalanche hazard conditions (Rathe, 1986).

However, definitive knowledge of the magnitude of sonic boom pressures required for, and probability of, triggering avalanches by sonic booms is entirely lacking. A previous attempt to trigger an avalanche by sonic boom was not successful (Lilliard, et al., 1965) due, apparently, to unsuitable weather conditions for avalanches at the time of the test. However, closely related information is available (Gubler, 1977) on the approximate required blast pressures from explosive charges used to trigger avalanches. Peak pressures of the order of 5 to 40 psf are indicated by the later data. However, lower sonic boom pressures may apply for two reasons:

1. The sonic boom N-wave may generate a higher effective response for the same peak pressure as the blast wave (evidence to this effect was shown earlier in Figure A-5).

2. A sonic boom carpet pattern would expose a much wider area than is possible by maximum explosive charges (approximately 2 kg of TNT) allowable for safety reasons for avalanche triggering.

Further research is clearly in order, especially in light of the consequences of unintentionally triggering an avalanche by sonic booms in a supersonic operating area occupied by recreationists in winter months.

Very substantial background information on snow avalanche mechanisms (Armstrong and Ives, 1976), forecasting and control (U.S. Department of Agriculture, 1968), and measurement (Armstrong and Armstrong, 1983, 1984) is available to support this research.

A somewhat similar situation exists for triggering of earth slides by sonic booms. One credible observation of a slide triggered by a sonic boom was reported by a National Park ranger (Holbrook, 1980). In this case, however, no information was located relative to explosively triggering an earth slide with relatively small surface charges such as for avalanches.

However, mechanisms of landslides (Terzaghi, 1960) are well-documented to aid in model development for analysis of sonic boom triggering potential for earth slides. The model would be based on definition of acoustically-induced soil stress levels comparable to those achieved by earthquakes which trigger landslides and is expected to show a low probability for triggering a landslide by a sonic boom.

A.5 LOW FREQUENCY RESPONSE OF STRUCTURES AND TERRAIN

The two areas of concern are: (1) the nondamaging response of buildings to very low frequency (e.g., nearly infrasonic) acoustic energy, and (2) nondamaging seismic response of the ground to this same type of excitation.

Response of buildings to low frequency noise (i.e., noise below 100 to 200 Hz) includes transmission of low frequency noise into the building. Very little data are available in this area since sound transmission loss studies of buildings or walls are customarily not obtained below about 100 Hz. Figure A-10 illustrates the range of one set of measurements by NASA at very low frequencies compared to an analytical model (Sutherland, 1982). The model includes features to account for sound transmission loss below the fundamental frequency for f_{11} of the primary

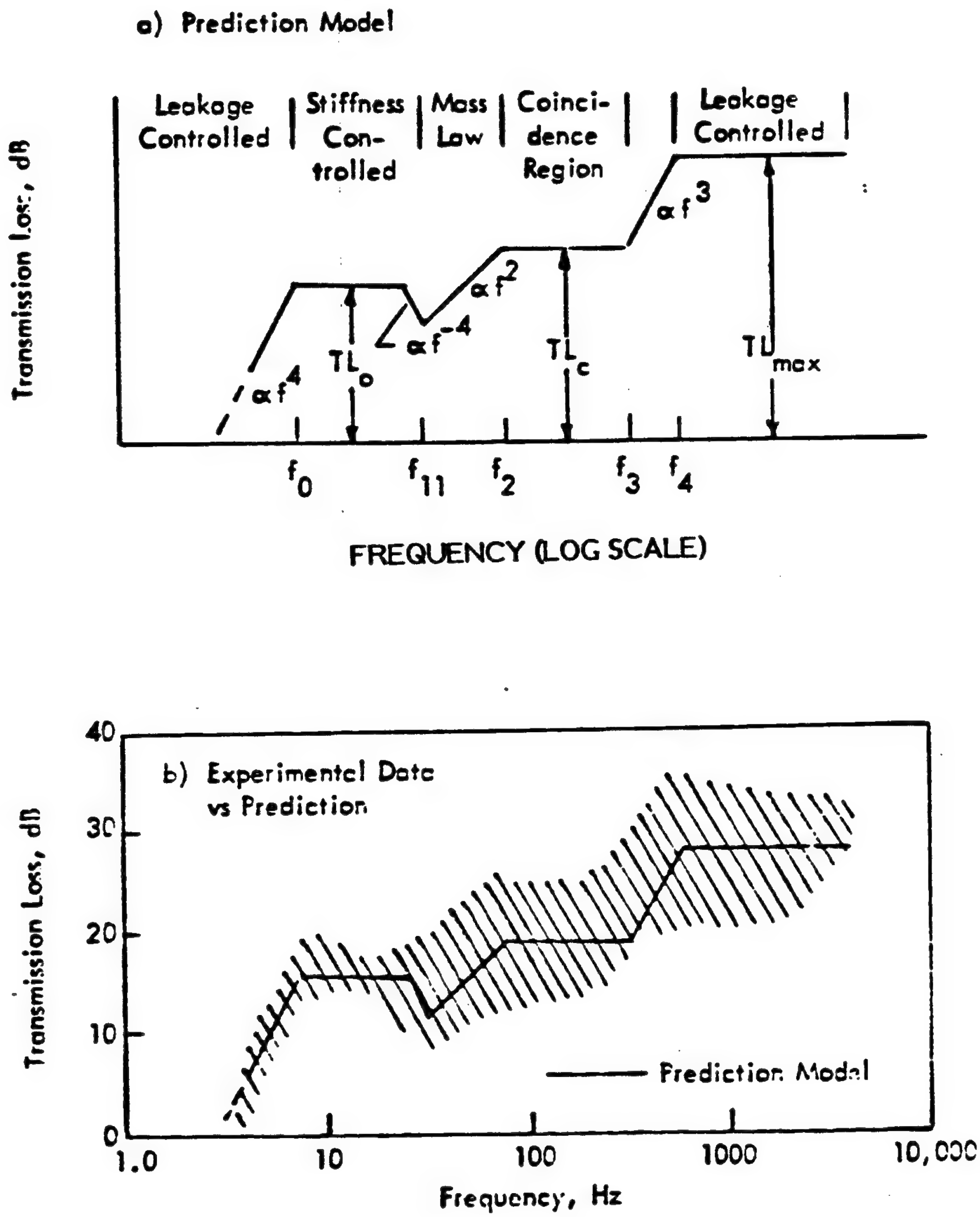


Figure A-10. Approximate Prediction Model (a) and Comparison with Experimental Data (b) for Sound Transmission Loss Into a Closed Volume (data from Stephens, et al., NASA TM 83288, 1982)

wall by including leakage effects which control transmission below a lower cutoff frequency (f_o in Figure A-10(a)) and sound transmission in the frequency range f_o to f_{11} where wall panels tend to be stiffness-controlled. The same sound transmission model involved in Figure A-10 could also be used to help evaluate the other and, probably more important, element of building response – vibratory motion of the walls. This motion leads to rattle noise generated when loosely-mounted objects such as picture or mirrors (see Figure A-11) or windows (Crandall and Kurzweil, 1968) rattle, or impact against a wall or window frame resulting in rattle or impact noise. The experimental work and "rattle" prediction models cited here, as well as recent breakthroughs on prediction of impact noise (Richards, 1979) will help in supporting development of the broader experimental data base, included in this Research Plan, than is currently available (e.g., Schomer and Neathammer, 1985).

A.5.2 Seismic Response to Low Frequency Acoustic Excitation

Recently, the subject of seismic excitation of the ground by low frequency acoustic energy has received considerable attenation to develop a better understanding of the propagation and detection of seismic signals generated by low frequency noise. Key results in this field by University of Mississippi researchers (Bass and Bolen, 1984) can be augmented by the related studies cited earlier concerning seismic response from sonic booms (e.g., Espinosa, et al., 1968) to provide an overall analytical foundation for this subject. The general trend of the more recent work indicates that seismic response patterns to acoustic excitation (in the absence of any coincidence effects) can best be explained in terms of a model for the earth consisting of a relatively thin (tens of centimeters) porous layer on top of a relatively impervious semi-infinite layer. The measured seismic response, and values predicted by this model, show a frequency variation (with maximum motion typically in the frequency range of 100 to 300 Hz) which is weakly dependent on the porosity and depth of the porous top layer, and the seismic velocities of the impervious underlayer. The gross seismic admittance (ratio of maximum ground velocity to acoustic pressure) observed and predicted by this model is comparable (approximately 1 in./second/1 psi) to values cited earlier in this appendix from many other studies.

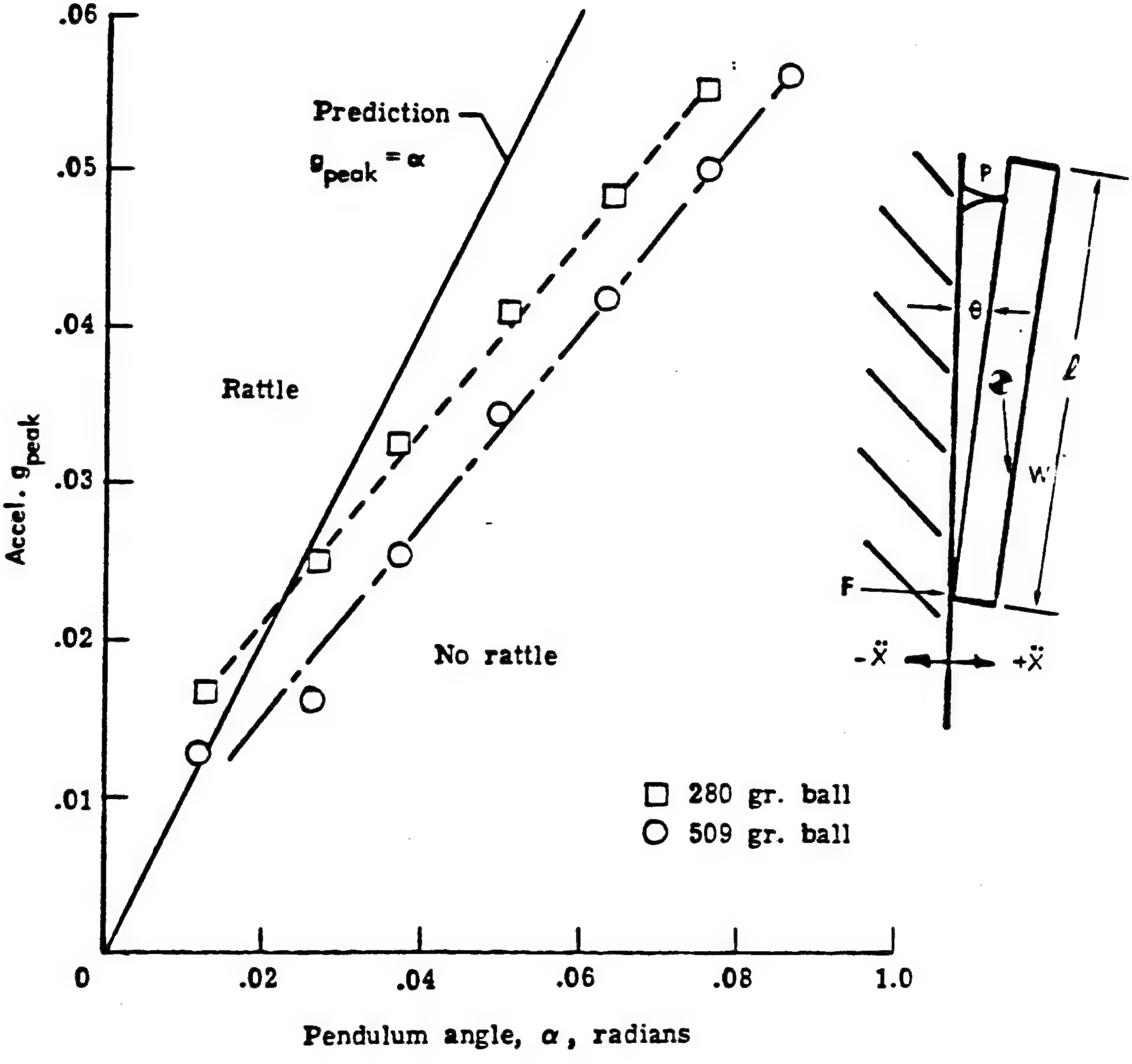


Figure A-11. Rattle Boundaries of Pendulums Resting with Various Hang Angles Against a Vibrating Wall (from Clevensen, S. A., NASA TM 78756, 1978).

APPENDIX B

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